THE US - CHINA SCIENTIFIC COLLABORATION, KNOWLEDGE MODERATION, AND CHINA'S RISE IN NANOTECHNOLOGY

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THE US-CHINA SCIENTIFIC COLLABORATION, KNOWLEDGE MODERATION, AND CHINA'S RISE IN NANOTECHNOLOGY

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation	Full Name
CKM	Chinese knowledge moderator
CKMA	Chinese knowledge moderated article
IC	International collaborator
ICA	Internationally collaborated article
CDA	Chinese domestic article
NLP	Natural Language Processing
MLP	Medium- and Long-Term Plan of S&T Strategic Development
RCS	Research Cohesion Score
GDP	Gross Domestic Production
PPP	Purchasing Power Parity
HEIs	Higher Education Institutes
S&T	Science & Technology
863 Program	National High Technology Research and Development Program
CUSPEA	China-US Physics Examination and Application
WoS-SCI	Web of Science: Science Citation Index Expanded

SUMMARY

In the emerging knowledge economy, scientific pursuit in the form of international collaboration has escalated. Studies consistently report that such collaboration, which has been intensifying in the last several decades, is common among not only advanced economies but also in emerging scientific nations such as China, India, and Brazil. The emergence of a “new invisible college” of international knowledge exchange has aroused interest from social scientists and captured the attention of policymakers. Indeed, recognizing its importance as a means of monitoring and exploiting other countries’ R&D investment, more and more countries champion and participate in international joint research.

International collaboration between the United States (US) and China is particularly interesting. The US has been and will continue to be the leader in scientific development for the foreseeable future. However, as a rising scientific power, China is changing the global landscape of ideas and innovation along with other emerging countries. The growing significance of the US-China relationship and worldwide interest in China’s development suggest that the characteristics of the scientific collaboration of these two countries and its associated knowledge dissemination across national borders are timely topics to study.

Surprisingly, few studies have examined research collaboration between a scientific superpower and an emerging scientific power, particularly in the context of emerging state-of-the-art technology. This dissertation seeks to address this research gap by examining patterns of collaboration in the US-China scientific community and its impact on China’s rapid knowledge accumulation in nanotechnology, if any, through

Chinese knowledge moderators (CKMs)—Chinese scholars who bridge two otherwise distant scientific communities through intensive collaboration with both sides.

The research focuses on the following three aspects: firstly, built upon the notions of the boundary spanner and the structural hole, the study develops the concept of Chinese knowledge moderators and uses it as an instrument to examine the relationship between international collaboration and knowledge spillover across national boundaries. Secondly, it operationalizes and tests the impact of US-China collaboration using multiple methods. In addition to citation-based indicators, based on the turnover of nanotechnology keywords, the study investigates the impact of collaborating with US scholars on CKMs' research trajectory and the international knowledge spillover facilitated by CKMs. Thirdly, utilizing a longitudinal publication dataset of 77 CKMs and their CV data, this study is able to quantify the dynamic impact of US collaboration on the quality of CKMs' research over time. The combination of bibliometric analyses, empirical testing, and case studies allows for the development of a comprehensive blueprint of US-China scientific collaboration in the field of nanotechnology.

This research yields several significant findings. First, the evolution of US-China collaboration in nanotechnology has gone beyond quantitative growth, as qualitative and structural changes have begun to take place. Secondly, CKMs play a critical role in fostering China's nanotechnology development, manifested in both knowledge creation and knowledge diffusion. The present study also reveals that US-China collaboration has a diminishing effect over time on the research quality of CKMs at level of individual papers, but as pertaining to entire journals. Thirdly, the case studies on the evolution of research streams suggest that US-China collaboration influences the research trajectory of

CKMs, who, as the conduits of knowledge, further disseminate it within the national boundaries of China.

The research also has policy implications for both sides. Chinese policy makers need to strengthen the mechanisms that encourage CKMs collaborating with the US, and, in order to amplify international knowledge spillover, these mechanisms should further encourage more interactions between CKMs and their Chinese domestic colleagues. From the US American perspective, given China's scientific emergence in nanotechnology, the US should direct its efforts to ensuring its ample access to exploiting the heavy R&D investment of this emerging scientific powerhouse by collaborating with top Chinese scientists.

CHAPTER 1

INTRODUCTION

Scientific Progress and Collaboration

Knowledge creation and diffusion are increasingly considered critical factors in national competitiveness. The central role of knowledge as an essential ingredient in economic growth is generally acknowledged by endogenous growth economists (Kline & Rosenberg, 1986; Lucas, 1988; Romer, 1990). Scientific progress, technological innovation, and knowledge diffusion foster sustainable economic development by extracting more output from the same amount of input and by converting what otherwise would have been waste into useful resources (Inkster, 1991). This is particularly important considering the fixed nature of a nation's or region's assets. Among the various means catalyzing scientific progress, research collaboration within and beyond national borders is often assumed to be an effective mechanism for amplifying the benefits provided by scientific achievement within countries and for exploiting other countries' R&D investments (Adams & Wilsdon, 2006).

Historical Perspective

The history of science and technology has witnessed how the efforts of countries to catch up to other more advanced nations are linked to their endeavors in science production and knowledge diffusion. For example, in seventeen-century Europe, as a result of the revocation of the Edict of Nantes, many French Huguenots fled to England (~80,000 people) and Germany (~30,000 people). Such mass migrations of skilled workers and intellectuals, while a great loss to France, greatly facilitated the development of science, industry, arts, and intellectual exchange in the United Kingdom and Germany in the eighteenth and early nineteenth centuries (Broadberry, 1998; Inkster, 1991).

The rise of the United States in scientific leadership also owes much not only to immigration but also to scientific exchange. In the nineteenth century, Germany led in many areas of science (Inkster, 1991). During this period, many US professors of chemistry and chemical engineering were educated in German universities, while US American students in chemistry were required to learn German in order to better assimilate knowledge produced in Germany (Drezner, 2001; Broadberry, 1998). This extensive period of exchange helped the US to build up their scientific capabilities in these fields and prepare the ground for subsequent US dominance in science in the twentieth century.

Global Trends in Research Collaboration

In the twenty-first century, knowledge exchange and diffusion across borders clearly continues, although new patterns are emerging. Teamwork, the internationalization of science, and the changing research landscape with the emergence of the scientific powers comprise three features of the changing mode of knowledge production and dissemination (Jones et al., 2008; Schubert & Braun, 1990; Wagner, 2008). The rise of digital libraries and dramatic reduction in communication costs due to IT development and the Internet's popularization are making idea cross-fertilization and technical expertise transfer much easier even without the establishment of designated institutions or facilities (Barjak, 2006; Laband & Tollison, 2000). Studies consistently report that science is becoming increasingly global in the emerging knowledge economy evidenced by dramatic increases in international collaboration over the last several decades (Arunachalam, Srinivasan, & Raman, 1994; Katz, Hicks, Narin, & Hamilton, 1996; Qin, 1994).[1] The intensified international collaboration not only holds for the advanced economies (Adams &

[1] The European Commission (2003) found more than 740,000 international co-publications were indexed in the Thomson Reuters databases in the period of 1996–1999. Wagner (2005) noted that 15% of global publications in 1998 alone were internationally collaborated articles.

Wilsdon, 2006; European Commission, 2003; Persson, Melin, Danell, & Kaloudis, 1997) but is also becoming more evident in emerging scientific countries such as China, India, and Brazil (Arunachalam, Srinivasan, & Raman, 1994; Basu & Aggarwal, 2001; Hwang, 2008; Velloso, Lannes, & Meis, 2004; Royle, Cole, Williams, & Evans, 2007; Rubinstein, 2000; Vogel, 1997). This emergence of a "new invisible college" of international knowledge exchange has aroused interests from social scientists and captured the attention of policy makers (Wagner, 2008).

Theoretic Debates on Research Collaboration

The exploratory work on research collaboration can be traced back to the mid-20th century (Simmons & Davis, 1957; Wellhausen, 1950; Wiseman, 1953). Since deSolla Price's seminar piece *Little Science, Small Science* (deSolla Price, 1963) this subject has received much attention across different fields. Extant studies on collaboration can be categorized into three research streams with evolving foci. The first strand of research discloses the global phenomenon of increasing co-authorship and defines the concept and scope of research collaboration (deSolla Price, 1963; Katz & Hicks, 1997; Laudel, 2001). Subsequent studies try to explore the contributing factors, benefits, and costs of joint collaboration. Some representative work includes Beaver (2001), Katz et al. (1996), Katz & Martin (1997), and Melin (2000). With the development of large-scale publication databases and scientometric analysis, various evaluative bibliometric measures are developed to gauge the relationship between research collaboration and research performance based on scientists' output (Lewison & Cunningham, 1991; Moed, 1989; Moed et al., 1985; Zhang, 1994).

It is generally accepted that on average collaborated articles are cited more than papers by single authors (Glanzel, 2002; William, et al. 2006). Two broad classes of explanations have been proposed to explain this phenomenon. The first perspective falls into the theoretical framework of intellectual human capital. Focuses on personal traits of productive scientists, Fox gave a detailed summary on the relationship between individual characteristics and research performance (Fox, 1983). Proponents of human capital explanation argue that the scientist, or knowledge carrier, who determines intellectual performance as reflected in their research articles. That is to say, a different set of skills and abilities of scientists embedded in multi-authored papers is the main factor of their job performance (Simonton, 1999; Simonton, 2004). And the more these eminent scientists have published, the more likely they are cited by themselves and their colleagues.

In contrast, the other perspective explaining the difference of research quality relates to social capital: people who do better are those who are better connected (Cohen, 1990; Burt, 2004). The brokerage position advocates suggest that people sit at the structural hole, i.e. at an intersection of two or more homogenous groups have access to different flows of information, and thus are more likely to generate better and novel research (Burt, 2005; Burt, 2004; Ahuja, 2000; Rodan & Galunic, 2004). In the view of Thorsteinsdottir (2000) and Meadows (1974), the new production of scientific knowledge is becoming more transdisciplinary and boundary spanning. Such processes of cross-fertilization of minds bring in additional expertise, are more reflexive, and thus cited by their colleagues (Lee & Bozeman, 2005).

Although both perspectives provide some insights into the variance of research quality, neither is complete. Built upon the existing literature, this project developed a concept of knowledge moderator (KM) to incorporate both arguments, and then differentiate people versus position effect through the combination of cross sectional and longitudinal regressions.

China's Emergence in Science

We will now shift our gaze to China for the following sections. China is deemed one of the most important emerging scientific leaders. All fields considered, China is the second largest contributor in terms of knowledge creation. The number of Chinese papers indexed in the Web of Science database increased at an average annual growth rate of 20% between 2001 and 2006 (*China Statistical Yearbook,* 2008). In EI Engineering Village, a more engineering-oriented database, the number of Chinese papers also increased from 18,600 to 65,100 during the same period, indicating an average annual growth rate of 50% (*China Statistical Yearbook*, 2008). Before hailing the rapid increase in the number of publications in China, one should bear in mind that knowledge production has been growing exponentially in numerous countries and disciplines. Taking that into account, China is still an outlier in terms of growth in scientific output. Continuing an upward trend in both scientific pursuits and global share from 1.4% in 1990 to 8.8% in 2006, China is unique among the seven most productive countries in scientific output (APPENDIX A.1).

China's astonishing publication activity is particularly reflected in the emerging field of nanotechnology. Measured by the number of nano research articles, previous studies have consistently shown that China is now the world's second largest producer in this nascent domain (Hullmann, 2007; Kostoff, Koytcheff, & Lau, 2007, 2008; Zhou & Leydesdorff, 2008).[2] In terms of citations, the research visibility of Chinese nano research is also increasing over time (Youtie, Shapira, & Porter, 2008).[3] China's growth in science and technology has aroused considerable interest among outside observers, and various reasons have been advanced to explain this phenomenon. Among them are the resources generated by China's fast-growing economic development, high levels of human capital, and the technocratic policy push (Suttmeier, 2008; Tang & Shapira, 2008).

[2] Some studies argue that China publishes more academic papers on nanotechnology than any other country (Kostoff 2008; EIU report, 2009).

[3] In this study, citation is an indicator of research visibility when it is used alone. However, it is referred to as a barometer of research quality, controlling for other factors influencing citations. For more detailed discussion, please refer to Chapter 4.

Contextual Factors of China's Rise in Science

China's Fast-Growing Economic Development

Since the inception of the Open-Up policy, the key indicators of China's economic health continue to exhibit remarkable growth, especially when compared to the growth rates of other countries. China's gross domestic product (GDP) in 2008 topped 30 trillion Chinese yuan (USD 4.39 trillion).[4] In terms of purchasing power parity (PPP), China has ranked as the second largest economy in the world after the US since 2007.[5]

The fast accumulation of wealth has provided the Chinese government with greater capacity to escalate R&D funding. Although China's R&D expenditures were initially low, their share of GDP has been growing significantly over the past decades. Indeed, China's spending on research has increased by more than 20% each year since 1999. Such growth is even more impressive given that China's GDP has simultaneously grown at close to a double-digit rate every year on average (Adams & Wilsdon, 2006). In 2005, China edged out Japan and became the second largest investor in R&D at USD 113.2 billion (current PPP US$), second only to the US. In 2007, China's R&D investment reached 1.49% of the GDP, up from 0.7% in 1998. It is now third in the global league table in terms of actual expenditures behind the US and Japan. As set out in the Medium- and Long-Term Plan of Science &Technology Strategic Development (MLP), China is now aiming to further boost investment to 2.5% of GDP by 2020, reflecting its commitment to sustain its high growth rates through R&D expending. All of these circumstances

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[4] Conversions from Chinese yuan to US dollar to Euro throughout this study are based on the average daily exchange rate for the 31 December, 2008, as reported by the European Central Bank (USD 1= CNY 6.8346)

[5] Source: 2009 Government Work Report of China delivered by Premier Wen Jiabao at the Second Session of the Eleventh National People's Congress.

are creating “unprecedented possibilities in a rapidly diversifying research portfolio” (Adams, 2006).

<u>China’s Accumulation of Human Capital</u>

Accompanied by rapid economic development, China’s human capital is also growing rapidly, as evidenced by the expanding activities of higher education institutions (HEIs), the increased research performance of Chinese universities, and the absolute number of science and technology (S&T) personnel. According to figures released by the Ministry of Education of China in June 2009, China harbored over 2,700 institutions of higher education, accommodating over 20.2 million undergraduates and 1.3 million postgraduates. A recent ranking of the academic quality of universities by the *Times Higher Education* places three mainland Chinese universities in the top 50 universities in the world for natural sciences in 2007, which sharply contrasts with the lack of a single Chinese university in this group seven years earlier.[6] All disciplines considered, the *U.S. News & World Report* identifies five Chinese universities as part of the world’s top 60 universities in 2009.[7] According to the *China Statistical Yearbook on S&T 2008*, China was home to about 4.5 million S&T personnel and 1.7 million R&D researchers in 2007, second only to the US. The number of post docs in China increased as well. At the beginning of 2009, China had produced 45,000 post docs with 40% in engineering, 20% in science, and 10% in medicine (Zeng, 2008). These statistics provide a solid research base for China’s R&D attainment.

[6] The University of Science & Technology of China ranked 40th, Tsinghua University ranked 34th, and Peking University was positioned at 15th. The data are electronically available at http://www.timeshighereducation.co.uk/index.asp?navcode=92

[7] University of Hong Kong (24), Hong Kong University of Science and Technology (35), the Chinese University of Hong Kong (46), Tsinghua University(49), and Peking University(52). The electronic version of the data is available at http://www.usnews.com/articles/education/worlds-best-universities/2010/02/25/worlds-best-universities-top-400.html?PageNr=2.

Technocratic Policy Push

The supportive role of Chinese government policy relating to scientific advancement has been generally accepted. Echoing Deng Xiaoping's slogan that "Science and Technology are the Chief Productive Forces," the Chinese elites have embarked on a significant push to promote the development of technologies critical to China's economic development. From the National High Technology Research and Development Program (863 Program)[8] to the Torch Program,[9] and from China's Fifteen-Year S&T Development Guidelines[10] to the Knowledge Innovation Plan[11]he Chinese government has exhibited active engagement in utilizing technocratic policies to narrow the technological gap between China and the industrialized world. Backed by China's fast economic growth and increasing R&D investment, a tremendous amount of research funding

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[8] The 863 Program (高技术研究发展计划 or 863 计划): In March 1986, four Chinese scientists—Ganchang Wang, Dayan Wang, Jiachi Yang, and Fangyun Chen—co-wrote a letter to the Chinese central government appealing for the development of high technology. This proposal was later endorsed by Deng Xiaoping within the same month. That is the origin of the "863 Project." The 863 Program sponsors research in key high technology fields that are considered important for China's national development. Supervised by the National Steering Group of S&T and Education and managed by the Ministry of Science and Technology (MOST), this program supports research and development in selected high technologies, nurtures technological expertise, and establishes foundations for high technology industries (Tang & Wang, 2009).

[9]The Torch Program (火炬计划) was launched by MOST in August 1988. Focusing on the application of completed R&D and commercialization of market-oriented technologies, one main thrust of this program is to create High and Emerging Technology Industry Development Zones to cultivate high-tech clusters in China.

[10] China's Fifteen-Year S&T Development Guidelines (国家中长期科学和技术发展规划纲要: 2006–2020), also called "the Medium- and Long-Term National Plan for S&T Development 2006-2020" served as China's S&T development strategy for the first 20 years of the 21st century. This strategy suggests that, given the limited technological and financial resources, the Chinese government should focus on enhancing indigenous innovation capacity as an S&T development strategy over the next fifteen years. Resources are mobilized to some key fields that are deemed to have major socio-economic implications for China's sustainable development (ERAWATCH Policy Templates for China).

[11] The Knowledge Innovation Program (知识创新工程) was inaugurated by the Chinese Academy of Sciences (CAS) in 1998 to allocate additional resources to the most promising institutes and research fields of CAS. From its inception in 1998, KIP has aimed to improve the scientific performance of CAS and build it into China's pre-eminent S&T centre for innovation capability. The targeted research themes of the Knowledge Innovation Program (KIP) include information, biology, advanced materials and manufacturing, new energy sources, space and oceanography, the environment and ecology, and cutting-edge research in some strategic areas of basic science (ERAWATCH Policy Templates for China).

has been allocated to some priority areas in its national S&T strategic plan; nanotechnology currently tops that priority list.[12]

The Chinese government has also facilitated international educational exchanges with scientifically advanced economies. A variety of bilateral and multilateral cooperation agreements and programs such as the Sino-US S&T Agreement, the China-US Physics Examination and Application (CUSPEA) program, the Joint Fund on Major Scientific Equipment Research, and the EU-China Framework Programs, to name just a few, have been established in the past several decades. With the help of these programs, China has strengthened formal collaboration with western economies in many aspects, as evidenced by the rapid expansion of institutional collaborations. For instance, at the institutional level, the establishment of the Sino-Germany Joint Research Center, the Sino-US Joint Centers for Soil and Water Conservation and Environmental Protection, and the Society of Chinese Bioscientists in America (SCBA) demonstrates active research collaboration between Chinese research institutes and their counterparts in other advanced economies. The Chinese government has become actively engaged in fostering international research collaboration, particularly with the US, in deciding which fields, researchers, and areas should be given priority for postgraduate and scholarly exchange programs. These policies interact with each other and generate a population of scholars who

In addition to these top-down approaches initiated by the Chinese government, bottom-up collaboration, or self-organizing collaboration at individual levels, is also thriving. Responding to government policies, Chinese universities and research institutions have implemented specific measures to facilitate the development of nanotechnology to upgrade university reputation and

[12] The other three targeted areas are information and communication technologies, biotechnology, and life sciences.

strengthen global presence (Zhang, 2002). These efforts include hosting international nanotechnology conferences, establishing formal collaboration with foreign institutions, recruiting outstanding overseas scientists, and bestowing monetary rewards and promotions based on scientific publications. All of these measures interact and reinforce each other, catalyzing the accumulation of individual knowledge attained through both individual and collaborative learning. This further contributes to the overall development of nanotechnology research at an aggregated level in China. As a result, China publishes more academic papers on nanotechnology than any other country with the exception of the US (Zhou & Leydesdorff, 2006; Youtie et al., 2008; Kostoff et al., 2008; Tang & Shapira, 2011). Figure 1.1 depicts the contributing factors of China's science and technology development.

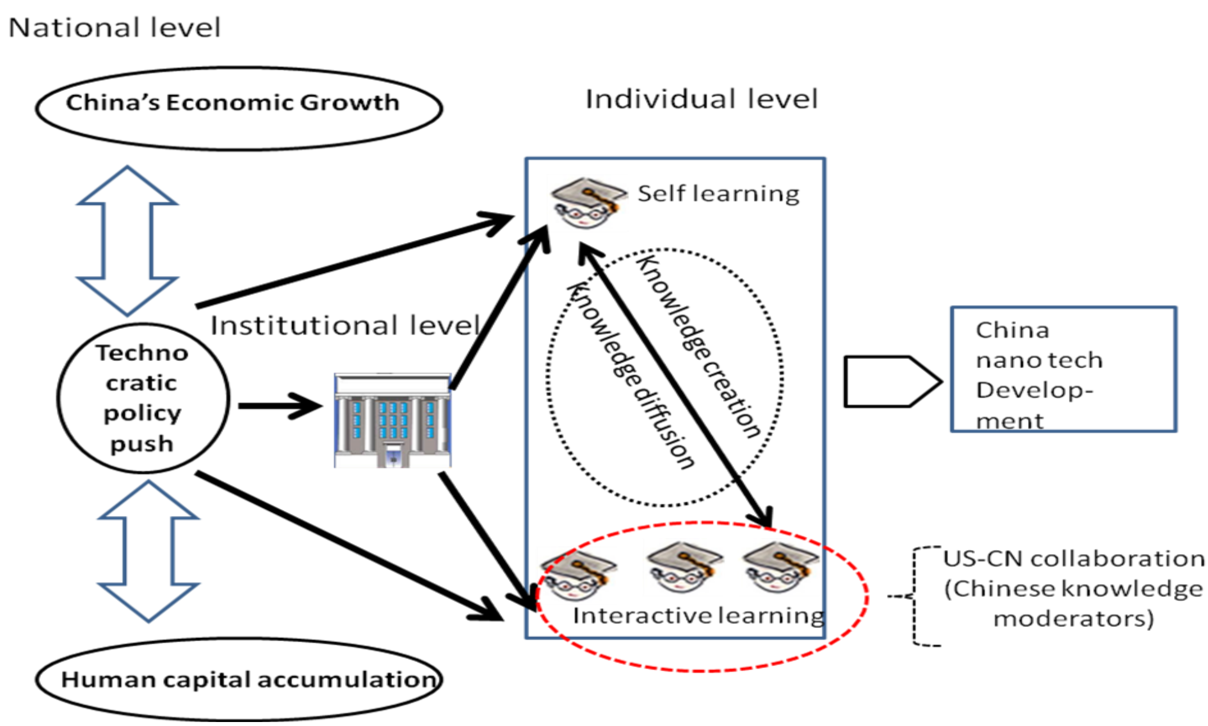

Figure 1.1 Contextual factors of china's rise in science

The fourth factor: The knowledge spillover associated with international collaboration

Except for the above three contextual factors that are generally agreed upon, similar to the development path of Britain, Germany, and the US, knowledge spillover associated with international collaboration is often presumed to be another salient reason for China's rapid development in science. Until now, however, this causal relationship has only been assumed and not been investigated empirically. In an attempt to contribute to the body of empirical knowledge in this research area, this dissertation will examine the role of the international collaboration between the US and China in driving China's rapid accumulation of knowledge from the window of Chinese knowledge moderators (CKM), a concept developed in this project.

Research Question

It should be noted that the purpose of this dissertation was not to examine the full story of nanotechnology development in China, nor was it to conduct a comprehensive study of all China-US scientific collaboration in this emerging field. These topics are too broad and complex to be addressed properly within one dissertation. Instead, by focusing on the research output of a specific group of Chinese nanoscientists, Chinese knowledge moderators, this study aimed to empirically investigate the impact of China-US research collaboration on China's rise in nanotechnology.

Specifically, I confined my examination to the following three interrelated research questions. Firstly, what are the patterns and dynamics of Sino-US scientific collaboration in nanotechnology? Secondly, what is the impact of Sino-US scientific collaboration on China's research quality? Thirdly, what is the impact of Sino-US collaboration on China's research frontier in nanotechnology?

Research Scope

Why US-China collaboration?

China is increasingly recognized as an emerging scientific powerhouse. From the US American perspective, concerns have grown that China's enhanced research capabilities may pose a challenge to US American technological leadership; for example, a major report by the National Science Board concludes that US global leadership in science and technology is declining as foreign nations—especially China and other Asian countries—rapidly develop their national science and innovation systems. A recent article in the *New York Times* reports that China is stepping up efforts to lure home top Chinese scholars who live and work abroad. Considering the Chinese Diaspora, a growing phenomenon of scientific changes, the debates are intensifying over international collaboration and knowledge spillover and how they may contribute to China's potential science supremacy in the future.

In spite of the significant policy implications, surprisingly scant empirical work has been conducted to investigate the relationship between the scientific superpower and the emerging one. From an academic point of view, before discussing any policy implications on international knowledge spillover, I decided to explore first whether I could identify the presence of knowledge spillover as resulting from international scientific collaboration. If this relationship existed, the second question would address how this impacts China's rise in science.

The origin of scientific collaboration between the US and China can be traced back to the late mid-nineteenth century, when the Qing government selected students to study western technique and science in the US. Since then, many of China's best and brightest minds have journeyed west to pursue knowledge, study advanced science and technology, and seek personal well-being. More and more Chinese students are attending universities and working in research organizations around the world, and the US continues as the leading destination for Chinese students going overseas. While many of these students remain in the US after completing their studies, an increasing number have returned to China in the last two decades. For those who chose to stay, a majority still maintain links with their fellow compatriots in China. According to the *Open Doors Reports*,[13] in the academic year of 2006/2007, nearly 68,000 students from China were studying in the US, an increase of 8.2% from the previous year. Following India (83,833), China is second among leading countries of origin for students coming to the US (Table 1.1). In 2009, one out of seven doctoral degrees granted in the US were conferred on Chinese students, 92% of whom had majored in science or engineering (Committee of 100, 2010). Conversely, with the rapid development of the Chinese economy, more and more western students and scholars journey eastward, temporarily or permanently, to undertake research in Chinese universities or to work at multinational enterprises (MNEs) in China. Peking University alone harbors about 4,000 international students and scholars—2,700 of whom are pursuing degrees. Bridging the "invisible" colleges in the East and West, these foreign-born or foreign-educated experts together with overseas returnees are assumed to contribute to knowledge dissemination on both sides.

Table 1.1: Historical Trends of Chinese Students in the US and US Students Who Study Abroad

Year	# of Students in the US From China	% of Total Foreign Students in the US	# of American Students in China
2007/08	81,127	13%	N/A
2006/07	67,723	11.6%	11,064 (up 25.3%)
2005/06	62,582	11.1%	8,830 (up 38.2%)
2004/05	62,523	11.1%	6,391
2003/04	61,765	10.8%	4,737
2002/03	64,757	11.0%	2,493
2001/02	63,211	10.8%	3,911
2000/01	59,939	10.9%	2,942

[13] The reports are published annually by the Institute of International Education with support from the U.S. Department of State's Bureau of Educational and Cultural Affairs.

1999/00	54,466	10.6%	2,949
1998/99	51,001	10.4%	2,278
1997/98	46,958	9.8%	2,116
1996/97	42,503	7.8%	1,627
1995/96	39,613	8.7%	1,396
1994/95	39,403	8.7%	1,257

SOURCE: Open Doors Reports, 2009. Institute of International Education, New York.

The role of foreign-born scholars in the development of science in the US has been widely documented. For instance, Levin & Stephan (1999) found that foreign-born and foreign-educated scientists and engineers make exceptional contributions to US science (Levin & Stephan, 1999). Similar results have also been disclosed by Tanyildiz (2008) and Lee (2004), who found evidence that the US has benefited greatly from the inflow of foreign talent. Surprisingly, very little empirical work has been conducted on their role in China's research development. Thus, this dissertation attempted to narrow this gap by focusing on Sino-US knowledge moderators in the context of the fast-growing field of nanotechnology.

Why Nanotechnology?

The focal field of this project was nanotechnology, an interdisciplinary field that involves manipulating molecular-sized materials to create new products and processes with novel features with nano-scale properties.[14] The selection of nanotechnology as the focus of this research was justified by three reasons: the social and economic importance of this emerging field, tremendous investment in nanotechnology in many countries, and the availability of data. Heralded as a promising field, nanotechnology is expected to heavily influence socio-economic development

[14] According to the National Nanotechnology Initiative definition, the size of research objects, that means, sizes on the nanometer level, and unique properties due to their size are two components of nanotechnology research.

(Roco & Bainbridge, 2005; Zucker & Darby, 2007). Accordingly, many countries have prioritized nanotechnology on their national research agenda (Roco, 2005); the US and China are no exceptions. These factors combined made this domain an ideal setting for studying the impact of international collaboration on research performance.

The remaining parts of the dissertation proceed as follows: the methodology section (Chapter 2) describes an integrated approach addressing research questions. Data cleaning and standardization, operationalization of CKM, as well as the comparison with other related concepts in the extant literature are presented here. Chapter 3 explores the patterns and dynamics of the China-US collaboration in nanotechnology. Chapter 4 outlines the empirical testing of the impact of the China-US collaboration and knowledge moderation on the research quality in China. Chapter 5 presents software-aided semantic analyses of the impact of US-China collaboration on the CKMs' research development. Chapter 6 synthesizes the findings of this study, discusses its policy implications, and concludes by outlining the contributions and limitations and suggesting future research directions.

CHAPTER 2

METHODOLOGY

Research Design

In order to address the above questions, a three-phase research design was adopted in this study. In the first phase, quantitative bibliometric analyses were used to profile the dynamic patterns of China-US collaboration in nanotechnology. Building upon findings in this phase, three sub-areas of nanotechnology were identified for the selection of CKMs (Chapter 3). In addition, the descriptive statistics of Sino-US collaboration led to hypotheses for testing, as detailed in Chapters 4 and 5. The second phase entailed CKMs identification and the compilation of their CV and publication panel data.[15] Statistical testing was then employed to examine the impact of China-US collaboration and knowledge moderation on research quality. In the third phase, a software-aided semantic analysis was adopted to document the turnover of nanotechnology keywords in the corpus of CKM articles (CKMA). Probit regressions were conducted to test the linkage between the shift of research topics and the advent of international collaboration. Three cases were selected to illuminate the role of international collaboration as a knowledge conduit between the research communities in the US and China. Figure 2.1 illustrates how the three-phase design was consolidated for analysis.

[15] The two terms *panel data* and *longitudinal data* are used interchangeably.

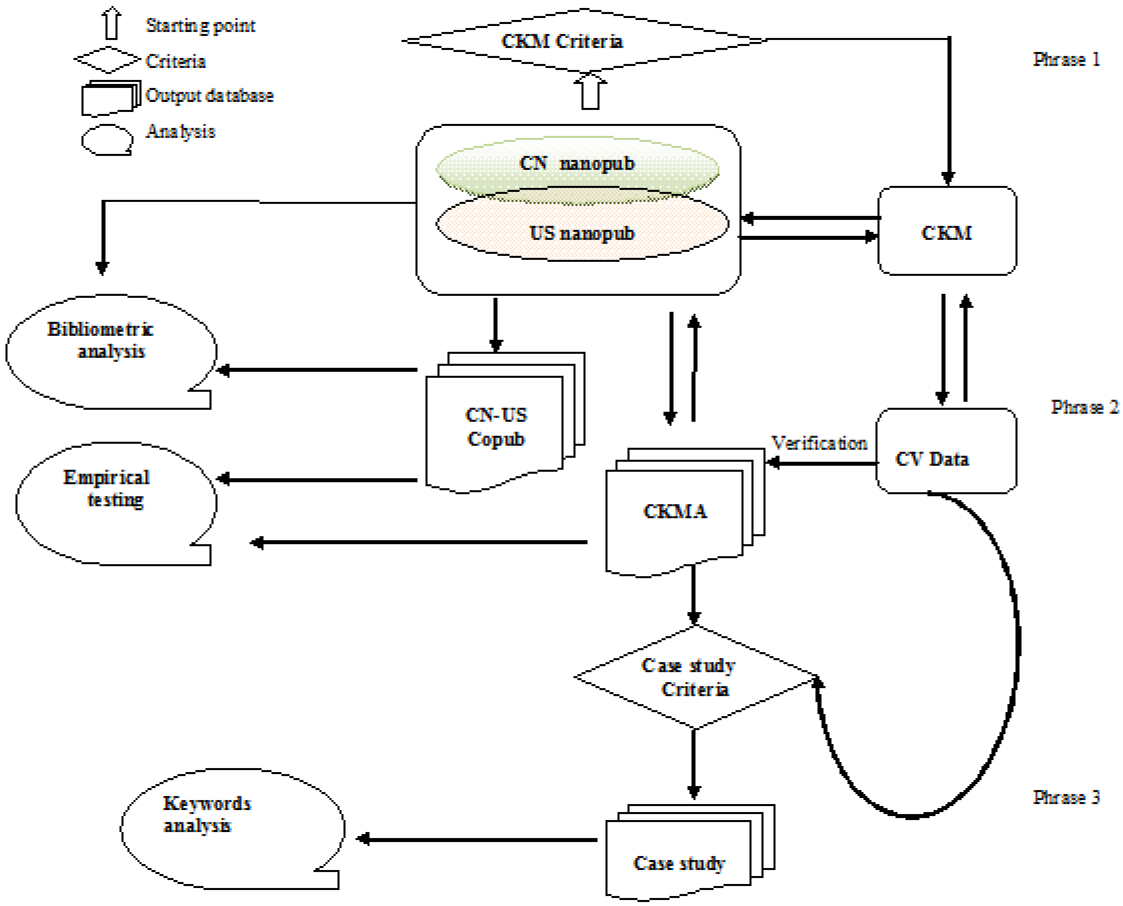

Figure 2.1 Database integration

Data

Nanotechnology Publication Dataset

The major data source of our analysis was nanotechnology publication data indexed in the Web of Science database. The publication dataset utilized in this project was constructed in the summer of 2006.[16] Built upon the nanotechnology search strategies of previous research (Kostoff et al., 2006; Zhou & Leydesdorff, 2008; Heinze, Shapira, Senker, & Kuhlmann, 2007), a two-stage composite Boolean search strategy validated by nanoscientists was developed by Science, Technology, and Innovation Program (STIP) researchers at the Georgia Institute of Technology. The strategy was applied to the Web of Science: Science Citation Index Expanded (WoS-SCI), the most recognized publication dataset in academia, and the global publications of nano research from 1990 to 2006 inclusively were downloaded in June 2006. In order to include the most comprehensive set of possible records, nano-related keywords were searched in the four fields of the raw records of articles: title, abstract, journal name, and author's keywords. After removing duplicates based on a unique paper identification number for each article, two sets of exclusionary terms were applied to remove records that had weak linkage with the National Nanotechnology Initiative definition of nanotechnology (NNI). The final dataset included about 430,000 world records, which were saved in 16 files according to year due to PC processing capacity. Appendix B.1 lists the search strategy. For a detailed description of this two-stage module method, please refer to Porter, Youtie, Shapira, & Schoeneck (2008) and Youtie et al. (2008).

[16] The raw records of the Georgia Tech Nanotechnology Publication Database have been updated in January 2010, and the coverage now is expanded from 1990 to 2009. But data validation and cleaning has not proceeded yet. Thus without specific indication only, only validated data from 1990 to mid-2006 is used in this project.

This study defines a Chinese publication as an article containing at least one Chinese[17] address given in the byline of that publication. Similarly, the term *China-US collaborated paper* refers to an article that includes at least one Chinese and one US address. The records that met these definitions were extracted from the 16 world nanoscience datasets and merged into one file. The bibliographic data retrieved from the WoS was enriched by information on the regional origin gathered from Web sites and integrated into the publication dataset. The WoS database collects various types of documents, including articles, reviews, corrections, letters, and so on. Only original journal articles (comprising 98% of all types of documents) were included in the dataset to maintain consistency among analysis results. The final dataset contained 43,767 Chinese NST including 2,051 joint China-US records. All of these records were first downloaded as raw text[18] and then transformed into VantagePoint text mining software for cleaning and bibliometric analysis. Figure 2.2 illustrates the workflow involved in the construction of the China-US nanotechnology publication dataset. Appendix B.2 lists the available information for US-China joint publications in WoS.

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[17] The geographical coverage of the publications is mainland China and two special administrative regions, Hong Kong and Macao. Due to their distinct S&T managing systems, Taiwanese publications are not included in this paper.

[18] Since WoS allows only 500 records downloading each time, we combined those 500's into a yearly publication dataset via VantagePoint.

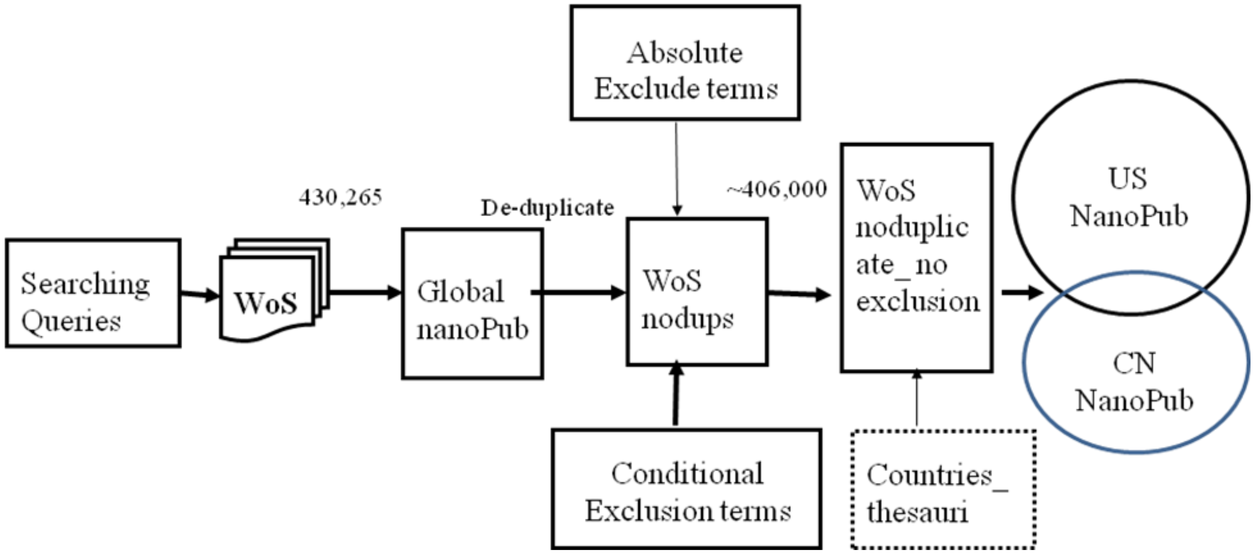

Figure 2.2 Construction of China-US nanotechnology publication dataset

Standardization of Publication Records

In spite of its value for research assessment, publication archival data has many pitfalls that need to be addressed while tracing scientific advancement and knowledge diffusion. Typical challenges include the inconsistency of bibliographic formats, optical character recognition (OCR) scanning errors, transliteration problems, and import filter parsing errors (George, 2006). As Hood and Wilson (2003) pointed out, bibliographic databases pay little attention to standardizing authorship-related information across different journals. Some bibliometricians have appealed for the necessity of "consistent and standardized indicators" (van Raan, 2004; Wallin, 2005); however, the practice of "editing or standardization processes and an overall scrutiny" (Melin & Persson, 1996) is largely ignored. Consequently, data must be handled and cleaned with care as a prerequisite for valid bibliometric analysis.

A careful review of the downloaded papers disclosed that bibliographic information in research papers was rife with errors of all kinds. For the purpose of this study, three fields were specifically targeted for cleaning and standardization: 1) affiliation locations (city, country) and affiliation names; 2) selected CKM and CKMC author names; and 3) nanotechnology keywords. Before analysis, the above fields were submitted to three stages of sequential cleaning (Raffo & Lhuillery, 2009). The first stage focused on mechanical errors such as misspellings, hyphenation, capitalization, different name formats, and so forth. This stage was automatically completed using the most conservative thesauri and fuzzy files embedded in VantagePoint software. The second stage consisted of manually checking for two types of errors: false positives and false negatives, which were either neglected or introduced by automatic cleaning.[19] The final stage

[19] For a false positive error, for example, manual checking is needed in order to remove wrongly allocated Chinese articles that contain the word "China" in the full affiliation addresses such as China Lake, CA, USA, Gatchina, Russia, and Hitachinaka, Japan.

consisted of validating based on complementary resources beyond the archival data. In addition to the above three-phase standard cleaning process, the cleaning of each field was dealt with differently according to its unique problems.

This section below focuses on geographic information cleaning. Although WoS was accepted as the most standardized publication dataset, the data showed that about one-fifth of Chinese nano records have different levels of within- or cross-record inconsistency among ZIP codes, city names, and/or country name fields. In general, the problems fell into the following four categories:

Missing data: Among the Chinese nano papers, 2.8% of the records reported no city names and 11.6% had missing ZIP codes.

Typographical errors: A considerable number of typographical errors occurred in affiliation names and related geographical information. On the international level, some records from Japan, Korea, Singapore, and Thailand without Chinese authors were attributed to China.[20] Domestically, many Chinese records were wrongly assigned to Beijing.

Name variations: Variations in regional names were quite common in the Chinese publication dataset. For example, the Xizang Zang Autonomous Region was sometimes abbreviated as *Xizang*, translated as "Tibet"; Xi'an, the capital of the Shaanxi Province, was often written as Xian; Guangzhou was also called Canton.

Data inconsistency across records: Due to the different levels of geographical units reported by authors, data inconsistency across different publication records was another considerable challenge for standardizing regional information.

[20] In addition, a number of articles produced solely by Taiwanese scholars reported China as an affiliating country. Given the distinct S&T systems of mainland China and Taiwan, these articles are excluded from this study.

These four issues are correlated, and simply ignoring these issues would not only have endangered the validity of the productivity rankings on the macro-level but also lead to inaccurate variable coding on the micro-level and thus mar the accuracy of the analytical results. For a detailed description of the cleaning process, please refer to APPENDIX B.3.

CV Data

In conjunction with nanotechnology publication data, the second data source of this project consisted of the curriculum vitae (CVs) of 77 CKMs. These CVs were obtained in response to e-mail messages sent to 77 identified Chinese knowledge moderators and further validated through extensive Internet search. Those CVs provided additional rich information for tracing the academic career development of CKMs. Since these data were collected after tremendous manual work to identify CKMs, more details on CV data are presented following the CKM concept and measurement in the next section.

Concepts and Measurement

International Collaboration

Following common practice, this study adopted co-authorship involving researchers from different countries as an indicator of international research collaboration. It is noted that, although joint publications are widely accepted nowadays, the validity of using co-authorship as a measure of research collaboration has been questioned. For example, based on research collaboration between firms and universities, Lundberg et al. (2006) argued that the “uncritical use” of either co-authorship or funding as such an indicator might mislead readers and policy makers. In the context of Chinese nano research, it is a reasonable assumption that most research collaboration is finally presented in the format of a co-authored paper for the following two reasons: firstly, the source of most research funding in China is the public sector, which is particularly true for emerging sciences (such as nanotechnology research)—they top the list of government development priorities. Secondly, studies have found that most Chinese nano publications originate in universities and public research institutes, where the main goal of researchers is to publish—partially driven by the promotion system in academe and funding criteria in different levels of funding agencies (Shapira & Wang, 2009; Tang & Shapira, 2011).

Knowledge Creation & Knowledge Diffusion

Knowledge creation refers to "discoveries about phenomena that were not known previously" (McFadyen & Cannella, 2004 p. 735). This research used articles published in internationally peer-reviewed journals as an indicator of knowledge creation (Gonzalez-Brambila, Velosob, & Krackhardt, 2008; Stephan & Levin, 1991).[21] Accordingly, the three facets of knowledge creation—quantity, visibility, and research content—could be measured by the number of published journal articles, the cumulative number of citations, as well as keywords.

Knowledge diffusion, a term often used interchangeably with *knowledge transfer*, or *knowledge spillover*, is the process through which one network actor is affected by the knowledge or experiences of another (Argote & Ingram, 2000; Inkpen & Tsang, 2005). Different from knowledge creation, knowledge diffusion is more often assumed rather than observed or tested.

[21] Such scientific advancement is acknowledged at least by the journal editors and reviewers.

Table 2.1: Indicators of China's Nanotechnology Development

Research Development	Indicators	Knowledge Creation (observable)	Knowledge Diffusion (assumed)
Quantity	Publications/Co-publications	Peer-reviewed journal articles indicate created knowledge.	The process of joint research embeds idea fertilization among co-authors.
Impact/Visibility	Citations	The cumulative number of citations indicates the impact/visibility of created knowledge.	A citation indicates know-ledge flow from the cited paper to the citing paper.
Research Content	Keywords	New keywords are considered as a surrogate of a new concept.	The correlation of keyword turnover and collaboration indicates knowledge spillover.

This study proposed to trace knowledge diffusion utilizing archival data through three indicators: citations, joint publications, and keywords, which are not mutually exclusive. Citations, an established proxy of knowledge spillover, are built on the codifiable aspect of knowledge (Noyons et al., 2003). Researchers can acquire existing knowledge through publicly accessible publications or patents (Jaffe, Trajtenberg, & Henderson, 1993; Nahapiet & Ghoshal, 1998; Noyons et al., 2003; Polanyi, 1967), and a trace of knowledge spillover is identified in the reported references. For instance, if article A cites a previous article B, it is generally believed that knowledge spillover from B to A has taken place. Nevertheless, this citation proxy bears significant factors of unreliability given that researchers may simply cite "big shots" or people they see in person every day.

A more formal and stringent indicator of knowledge spillover is co-authorship. However, few studies have explicitly used co-authorship as an indicator of knowledge spillover. The rationale is built on the tacit nature of knowledge. Since a researcher has to make substantial and significant efforts to become acknowledged in terms of authorship, the co-authoring process instigates the cross-fertilization of ideas among individuals. One main concern regarding this indicator is the assumption that each co-authored paper is a collectively orchestrated product

(Frickel & Gross, 2005). On the contrary, idea fertilization among individual authors may not occur at all, especially when they come from multiple regions. For instance, if an article has ten authors affiliated with five different regions, it does not necessarily indicate that knowledge spillover has taken place between each pair of co-authors.

The third type of evidence or measure for knowledge spillover proposed in this project was the spatial shift of keywords. Taking keywords as a surrogate of a new concept, the correlation between keyword turnover and international collaboration indicates knowledge spillover across national boundaries.

As discussed above, knowledge creation and knowledge diffusion are two sides of the same coin, so they can be measured simultaneously by publication data. For example, the number of published papers indicates knowledge creation per se.[22] This publication can also be considered one indicator of knowledge diffusion if it involves more than one author and/or different geographical areas. Citation counts themselves are a measure of research visibility/quality, but if B cites A, this leaves traces of knowledge flow. Along the same vein, if we observe a shift in a research topic, it is a sign of new knowledge at the level of the individual scientist, and the observed correlation with collaboration and/or research mobility represents a barometer of knowledge diffusion. Utilizing the publication dataset, this study used the above three indicators to gauge the role of international collaboration and knowledge moderation (Table 1.2).

[22] Only original journal articles are considered for analysis in this project.

Chinese Knowledge Moderators & Knowledge Moderation

The term *Chinese knowledge moderators* (CKMs) refers to a specific group of Chinese scholars who connect the respective scientific communities of the US and China by co-authoring with both sides. By definition, a moderator is someone who mediates between parties at variance.[23] The key role of a moderator, namely moderation, includes introducing new topics and facilitating active discussion among different parties. In many cases of scientific research, moderators are also active participants. Drawing upon this notion, a China-US CKM is defined as a specific type of boundary spanner who bridges communities of scientists in China and the US and facilitates scientific communication via active collaboration with both sides.

<u>*CKMs Criteria*</u>

Two dimensions, the family name of the author and his collaboration experience, were used to identify CKMs. In this project, a nanoscientist was considered a CKM in China-US research collaboration if he or she satisfied the following criteria:

1) A Chinese family name
2) Co-authorship on at least two papers with US affiliation during the period of investigation
3) Co-authorship on at least two papers with Chinese affiliation during the period of investigation

The two-dimension coding was based on the following considerations. A CKM is a researcher who bridges two different scientific communities respectively located in China and the US via *intensive* collaboration with both sides. Given the tacit nature of knowledge diffusion, it is reasonable to believe the role of knowledge moderation is embedded in the *process* and the

[23] The definition of "moderator" or its synonym "mediator" can be found at http://www.merriam-webster.com/dictionary/moderator; http://www.merriam-webster.com/dictionary/mediator

result of joint publication in internationally peer-reviewed journals. Thus, the publication dataset could be used to identify knowledge moderators. Requiring that each side collaborate on two or more publications was arbitrary, but the main idea was to exclude sporadic or opportunistic collaboration and to reduce CKM verification tasks to a manageable level. My practice also embraced two conflicting notions in social network theory: the structural hole and trust cultivation via frequent interactions (Burt, 2004, 2005; Coleman, 1990).

Restricting knowledge moderators to only scholars with Chinese family names is justified for the following reasons: firstly, in order to make scholarly communication possible, the knowledge moderators must be able to communicate with scholars on the Chinese side. As noted in previous study, China's language and culture continue to present substantial obstacles to a non-Chinese researcher pursuing a career (Reynolds, 2006). Thus, assuming that individuals with a Chinese family name embed both cultural and language factors, they can communicate more effectively with scholars in China. In fact, evidenced by the dataset, less than 1% of the authors who appeared in the Chinese nano publication dataset have non-Chinese family names. Lastly and related to the first reason, restricting knowledge moderators to only Chinese scholars allowed me to comment on China's peculiar human capital policies: sending domestic Chinese researchers out (*gongfei chuguo kaocha*) versus luring self-sponsor expatriates back (*xiyin jifei haigui huiguo*).

<u>Comparison of CKMs and Other Similar Notions</u>

The notion and operationalization of CKMs is closely related to international collaborators. In bibliometric analyses, international collaborators and international collaborative articles are determined solely by reported authorship affiliation. If an article published at t_1

documents affiliations in two or more countries, that article is regarded as an internationally collaborative article, and *all* authors listed in that paper are regarded as international collaborators at t_1. Problems may occur, however, when the international collaborator migrates across national borders. In the case of overseas returnees,[24] for example, once they return home,[25] the knowledge spillover associated with their collaboration with domestic colleagues is *completely* and *immediately* veiled. The notion of the CKM can *partially* address this problem by focusing on researchers and knowledge carriers instead of papers alone. Thus, if an author is identified as a CKM, all of his papers will be counted as CKMA regardless of whether he or she remained in the US or whether he or she had already returned to China at the time of publication.[26] APPENDIX B.4 depicts the difference between CKMAs and ICAs.

In addition to the concept of international collaborators, other concepts illustrate the individual's role in knowledge creation and knowledge spillover, which has been extensively explored in the contexts of academia and industry. Such investigations have included star scientists, boundary spanners, knowledge brokers, and structural holes, to name just a few (Zucker, Darby, & Armstrong, 1998; Furukawa & Goto, 2006; Burt, 2005).

Positioning these notions on a two-dimensional coordinate system shows the connections of CKM with the other concepts and its uniqueness. As seen in Figure 2.3, the thresholds on both intellectual capital and social capital are imposed for people in this category of CKMs. Though CKMs may be star scientists, it is not a necessity condition identifying someone as a CKM. The demarcation line is whether the scientist has a high connectivity with both internal and external

[24] In addition to returned Chinese expatriates, this also applies to American researchers who undertake research in China.

[25] It is reasonable to believe that expatriates report their home country as their authorship affiliation when they return.

[26] For a further differentiation of CKMA based on whether it was published in the same year as the second internationally collaborated paper or thereafter, please refer to the statistical testing in Chapter 4.

knowledge sources. Chinese knowledge moderators can be regarded as a specific group of boundary spanners, people at the national boundary who connect two geographically distant scientific communities (Burt, 1992; Garcia & Smith, 2003; Nochur & Allen, 1992). However, the value of CKMs to the development of nanotechnology in China is not only that they themselves create significant scientific breakthroughs that contribute to China's knowledge stock. More importantly, they link China with outside scientific communities and synergize the technologies of two otherwise distant communities (Schilling & Kozin, 2009). Their unique position "generates new insights and supports exploration of new knowledge" (Crossan, Lane, & White, 1999) for both CKMs and Chinese collaborators (CKMC), and thus they catalyze China's overall nanotechnology development.

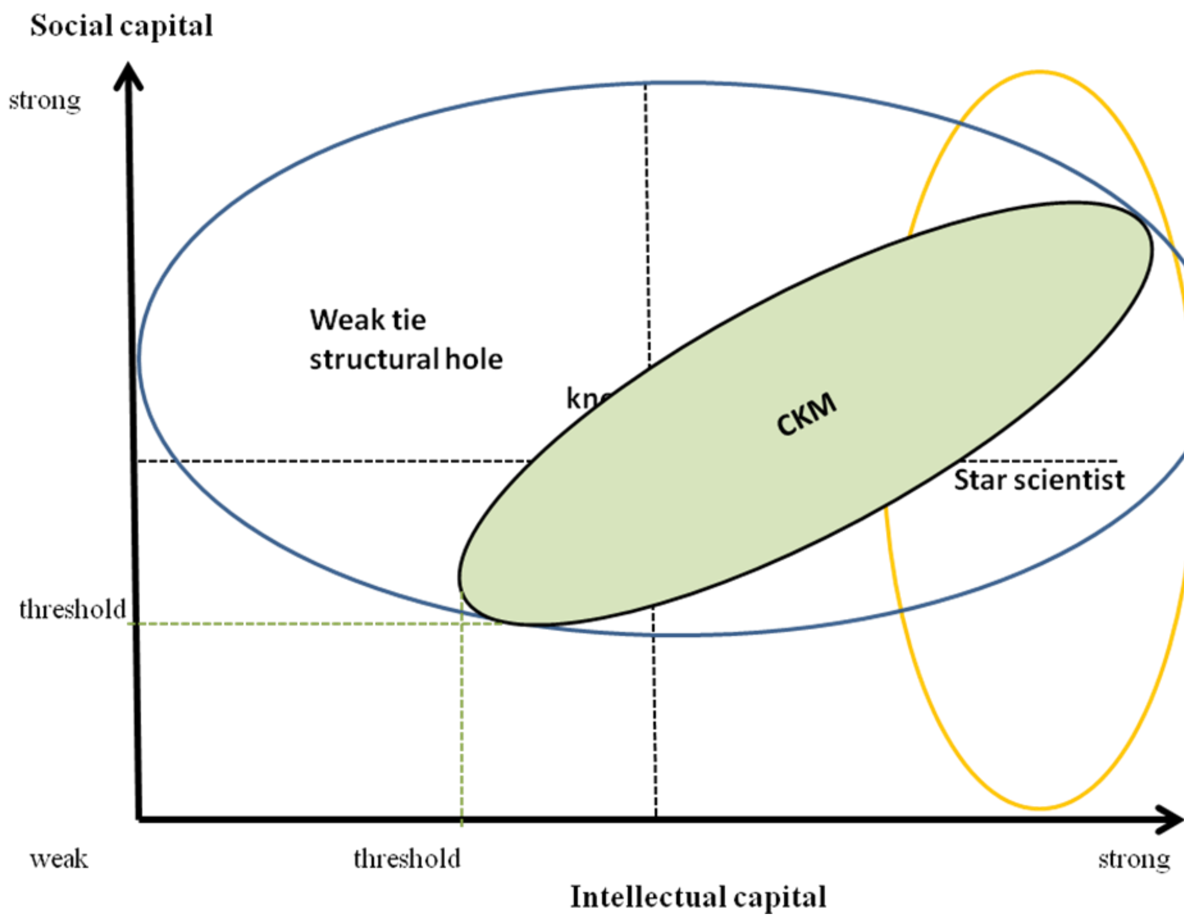

Figure 2.3 Comparisons of CKM and other notions

Identification of CKMs

Three Focal sub-fields in Nanotechnology

As converging technology operating at the nano-scale, nanotechnology consists of a set of interrelated disciplines. This study intentionally focused on three research domains: nano materials, nanobiology & nanomedicine, and nano electronics & nano devices for CKM identification. These domains were selected for two main reasons. One is based on the dynamics of the China-US research collaboration, which is discussed in Chapter 3. Focusing on these three sub-domains allowed me to investigate the role of CKMs in research domains where US-China collaboration frequently takes place. The other reason is that these three fields are particularly targeted for China's short-, medium-, and long-term development (Tang, Wang & Shapira, 2010), as announced in the *National Development Plan for Nanoscience and Nanotechnology (2001–2010).* Thus, the examination of knowledge spillover in these three fields is especially pertinent to policy implications.

Multiple-stage Boolean search strategies were adopted to define the boundaries operating on the fields of keywords relating to journals and nanotechnology, as illustrated in Table 2.2. The initial set of keywords was based on the pilot "field scope" definition developed by Georgia Tech researchers (Porter et al., 2008). Wild marks ("?"or "*") and Boolean logic were used to capture the variations in nanotechnology keywords such as plurals, extra spaces, hyphens, and term abbreviations. The wild mark "?" stands for a zero or one character, and "*" stands for one or more characters. Thus, "nano?tube" captures the words "nanotube," "nano tube," and "nano-tube," and "assembl*" can capture words "assemble" and "assembling." The table shows that, as reflected by nanotechnology publications, China's research is strong in nano materials, while relatively weak in nanobiology and nanomedicine research.

Table 2.2: Defining the Focal Fields of CKMs: Nano materials, Nanobiology and Nano electronics

	Nano materials	Nanobiotechnology & Nanomedicine	Nano electronics & Nano devices
Keywords	Nano?material? Nanoparticle? or Nano?particle or Nano?structured particle or Nano?powder TiO2 NPs or nTiO2 Carbon nanotubes or CNT? Or SWCT or SWCNT or MWCNT? Nano?composite oxide NP titanium oxide zinc oxide nZnO alumina or nAl2O3 C60 or Fullerenes Nano?gold or Nano?silver or Nano?crystal quantum dot?	Nano?bio Nanopharmaceutical Nanoscale drug Nano* microbial micro-RNA or mRNA nano AND biosensor Nanomedicine DNA Molecular Protein Sensor Drug (delivery or targeting or release)	Nano?electronic Transistor Single-molecule electronics Molecular (electronics or logic gate or wires) Communic* Comput* Nanocircuitry Nanowires Nanolithography NEMS Nanosensor Nanoionics Nanophotonic? Or Nanomechanic? Semiconductor
Journal	material* OR polymer*	bio* OR pharma* OR medic* cell* OR catalys* OR clinic* OR drug OR gene*	electron* or electri* computer* optic*
#Records	30431	6719	12530

CKM Identification

Due to the well-documented name ambiguity problem, authorship identification is highly challenging in large-scale publication databases. In general, two hurdles must be overcome. One is that one author may report different forms of his/her name, and the other is that identical names could represent different authors. Both situations lead to errors, albeit contrasting ones. In other words, while the former produces false negatives and understates the research activities of a researcher, the latter case yields false positives that overstate the publications of a targeted researcher. Given the tremendous number of researchers with the same family name (a vast majority of whose names are in the 50 most common family names), this problem is serious in studying China. In addition to the caveats of the publication database, various methods have been proposed for name disambiguation. In this study, by combining CV data, online searches, and verifications with CKMs, tremendous effort was extended to verify CKMs and their publications (CKMA).

Figure 2.4 depicts how the CKMs in the three domains of nanotechnology under study were identified from a specifically constructed nanotechnology publication database. Since all the CV data of the CKMs and all their affiliations had been collected, this study relied on the author name combined with the manual cleaning method to identify a CKM and extract CKMAs. I started with the names appearing twice in the China-US co-publication dataset. The field of "author" was first cleaned following the most conservative approach. With the idea of casting a wide net first, a false positive was temporarily allowed at this stage.[27] Authors with Chinese family names who appeared at least twice in different articles were considered CKM candidates.

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[27] If middle names were available and different, the authors were not considered the same. For example, in the first stage, "Pashley, DH" was considered the same author as "D H Pashley," "Pashley D," Pashley H," or "Pashley, HD," but not "Pashley, DD." Along the same vein, articles reporting either "An, L N" or "An, L" were considered the same author as "An, Li Nan" at this stage.

This CKM thesaurus, as shown in Figure 3.3, was then applied to the fields of author names in the Chinese publication dataset to extract publication records. This returned 374 potential CKMs associated with 10,191 articles that were retrieved from the Chinese nano dataset with 43,767 records.

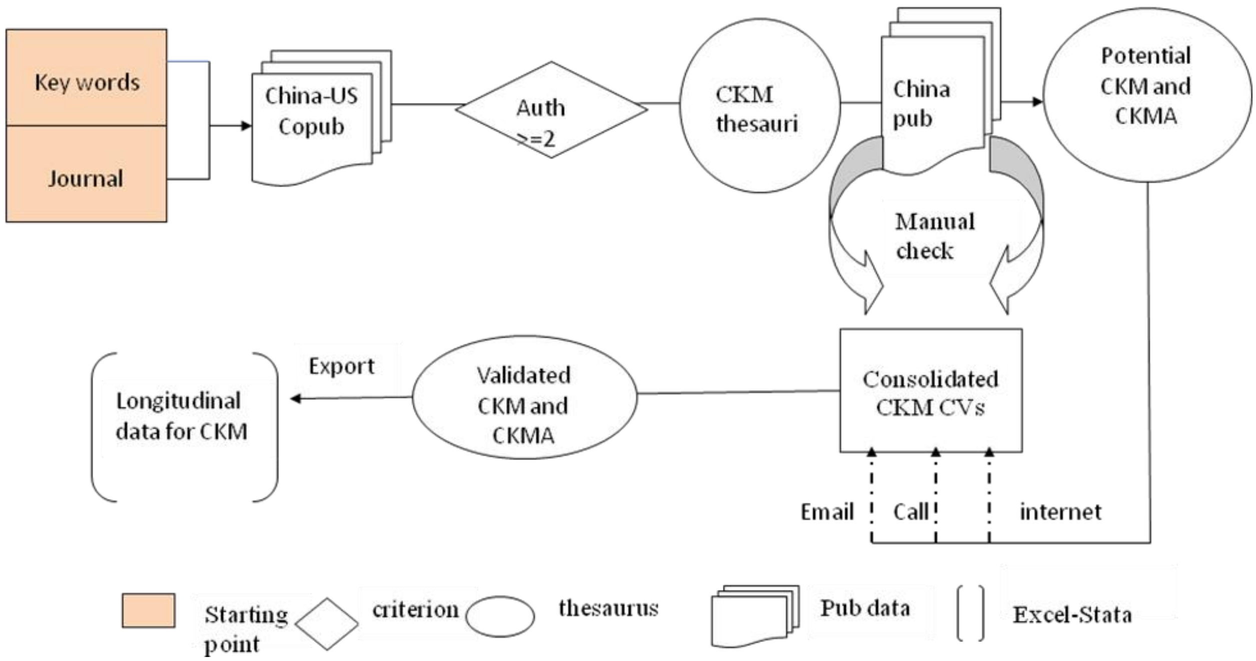

Figure 2.4 Flow chart for identifying CKMs and CKMA

In the second stage, starting with the most productive CKM candidates, the information of 96 potential CKMs was collected. In addition to the full record of their publications and cited references, comprehensive information about a CKM consisting of both academic and professional activities, if applicable, was compiled. More specifically, information such as gender, the sub-specialty within nanotechnology, the institutional affiliation, and professional experience outside of China (Franzoni, 2010) were collected. Based on CV information (both geographical information[28] and publication lists), both false negatives[29] and false positives were identified and handled separately. In addition, a cross check was conducted via the Scopus database[30] and fifteen verification e-mails[31] were sent out, resulting in only one non-response. After the manual checking process, 2,186 records were identified as those written by the 77 CKMs: in the three nanotechnology domains of nano materials, nanobiology, and nano electronics, 31 CKMs, 27 CKMs, and 27 CKMs respectively were finally selected. Once the CKMs were identified, the CKMAs, the articles co-authored by the CKM, were retrieved. Then a subset of publications was constructed for each CKM candidate. In our dataset, the 77 CKMs combined had co-authored 2,186 nano papers that reported a Chinese address. About 30% had a US American scholar as co-author, constituting nearly one-third of all China-US collaborative papers in the period of examination. This figure indicated the critical role of these 77 CKMs in China-US joint research, at least as measured by the quantity of research output. Appendix B.5 lists the publication counts before and after verification. As shown, the manual check suggested that only 20% of records were correctly identified if relying on reported author names from the Web of Science. Such tremendous differences in data before and after cleaning indicated an inflation of results of simply collapsing names from the Web of Science datasets. This also supported the findings of Newman (2001) and Tang & Walsh (2010), both of which call for specific attention to name ambiguity when utilizing bibliographical data for micro-level analysis.

[28] One rule of thumb dictated that if an author "Wang, Jin" never worked at or was affiliated with Florida State University, then the article with "Wang, J" appearing as the reprint author who reported Florida State University as his/her affiliation should not be included as list of papers for "Wang, J."

[29] A false negative occurs if inconsistent names of the same authors were reported, for instance, if a CKM named "Luo, Guo An" reported both "Luo, G A" and "Luo, G" in his publications, or if "Zhang, Jin" reported "Zhang, J Z" rather than "Zhang, J" in all his publications. These cases were verified with the CV of the CKM with and WoS nano publication lists.

[30] Searching the same articles in the Scopus dataset provides me with information on authors with their reported affiliations and e-mail addresses.

[31] In the verification e-mails, which were written in both Chinese and English, the authors were provided with two groups of publications—those were assigned to them and those were not assigned to them. The authors were asked to verify the assigned results.

Profiling Chinese Knowledge Moderators

The CV data, however, suggested that the CKMs in our dataset were a quite heterogeneous group, including not only established top-notch researchers but also rising young scholars. In this sample of CMKs, ranging from 28 to 74 years of age, the average age was 45. They were all born in China; they were predominantly male (92%); and a majority of them (about two-thirds) earned their doctoral degree at domestic Chinese universities. In terms of their positions, 61 were full professors, 7 associate professors, 5 assistant professors, and 4 senior researchers. Fifty-nine CKMs were currently working in China, and 18 were full-time researchers in the US. It is noted that some of the researchers currently residing in China were working at second-tier universities and in western China. Equally interestingly, all 9 tenured professors who were originally from the mainland had set foot in China and the US.

Another striking feature of these 77 CKMs was their international mobility. Surprisingly, their CVs disclosed that 76 out of 77 CKMs had studied or gained work experience overseas, and over 80% of their overseas visits had been funded by the Chinese government. In terms of their scope of collaboration, the average number of authors on all CKM nanotechnology papers had increased steadily over the period of examination, from an average of 4.3 authors per paper in 1990 to 5.4 authors per paper in 2006. These numbers did not significantly differ among the three domains. Not surprisingly, the preliminary descriptive statistics showed that, of the internationally collaborative articles, 98% were written in English. These statistics also held true for CKMAs without involvement of international scholars. Assuming that people who reside in foreign countries have a higher mastery of the English language, one incentive for domestic Chinese researchers to publish in international journals by co-authoring with international scholars is to compensate for one's language barrier through the help of a collaborator with (native) fluency. Another two competing explanations for the large number of articles written in English are the coverage bias of SCI-WoSwhich favors English, and the "open secret" that the Chinese science community favors and rewards publication in international journals.

CHAPTER 3

CHINA-US SCIENTIFIC COLLABORATION IN NANOTECHNOLOGY: PATTERNS AND DYNAMICS

Introduction

Nanotechnology Emergence in China and the US

Heralded as a promising field, nanotechnology is expected to heavily influence every facet of science, technology and socio-economic development (Roco & Bainbridge, 2005; Zucker & Darby, 2007). The National Science Foundation has estimated that the annual global market for nano-related goods and services will exceed $1 trillion by 2015 (Lee, Chan, Ngiam, & Ramakrishna, 2006). Accordingly, many countries have prioritized nanotechnology on their national research agenda (Roco, 2005); the US and China are no exceptions. Released figures show that federal funding for the National Nanotechnology Initiative (NNI) in the US has more than doubled in four years, increasing from $464 million in the fiscal year 2001 (FY01) to $1.1 billion in the fiscal year 2005. State governments and private sectors have also increased their investment in nanotechnology. In 2004, investments in nanotechnology from the private sector amounted to roughly $2 billion (*Nanotechnology: where does the U.S. stand*, 2005; Nordan et al., 2005). Following US American trends, China's investments earmarked for nanotechnology have been substantial. In 2005 alone, China invested $249 million in the nanotechnology field, more than 1% of its total R&D expenditures across all fields (Lux Research Inc., 2007). According to the statistics released by the European Commission Report (2005), China has invested ~540 million US dollars in this emerging field, ranking only after the US (1.7 billion US dollars) and Japan (~800 million US dollars).[32]

Realizing the significance of this emerging field, China's policymakers have enacted various policies and programs to spur R&D in nanotechnology (Tang, Shapira, & Wang, 2010). Such promotion efforts can be traced back to the ten-year "Climbing-Up" project, initiated in 1990. The National Steering Committee for Nanoscience and Nanotechnology (NSCNN) was established in 2000 to coordinate China's nanotechnology activities. In 2001, the Chinese government highlighted nanotechnology as a critical R&D priority in their Guidance for National Development. In the same year, the Compendium of National Nanotechnology Development (2001–2010), and the Nanotechnology Basic Research Program, both calling for a diversified research profile and commercialized nanotechnology (Zhou & Leydesdorff, 2006; Tang, Shapira, & Wang, 2010) were released.

China's massive investment in nanotechnology has led to quantifiable results. Reflected by research output, over 660,000 nanotechnology papers have been indexed in the Web of Science (WoS) since 1990.[33] The US has occupied the top position for many years. Surpassing Japan in 2001, China has become the second largest contributor as measured by nanotechnology articles produced annually. In terms of the collaboration scale, the US is China's preferred collaborator, and the Chinese have formed stronger and stronger links with US American nano researchers (Tang & Shapira, 2008; Youtie et al., 2008).

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[32] The European Commission Report gives accounts of figures in terms of Euros. The author exchanged them into US dollars at the rate of 1 Euro =1.35 US dollars.

[33] Data Source: Global Nanotechnology Publication Dataset 1990–2008, constructed by Georgia Tech researchers.

Analysis

China's Status in Nanotechnology Development

As noted, the Georgia Tech global nanotechnology publication dataset includes more than 400,000 WoS records in the period from 1990 to mid-2006. By volume, the top six most productive countries in descending order are the US, Japan, China, Germany, France, and the UK, constituting over 60% of the nano articles globally.[34] This finding is consistent with those of previous studies despite their distinct search strategies (Kostoff, Koytcheff, & Lau, 2007). In order to create a more detailed impression of the relative positions of the vanguard countries over the years, I divided global nanotechnology publication data into three subsets covering the periods of 1990–1995, 1996–2000, and 2001–2006.

Table 3.1 shows the relative changes in rank of the most productive countries. As seen, China ranked sixth in the world in terms of the amount of nanotechnology research conducted during the period of 1990–1995. This suggested that, contrary to a popular belief among western scholars, instead of a "latecomer" in nanotechnology, China, in fact, has occupied a vanguard position since the early 1990s, at least in terms of research output. In addition, unique among the original 10 most productive countries (1990–1995), China demonstrated a growth trend: its global share of 4.0% in the period of 1990–1995 increased to 15.2% in the period of 200–2006. Remaining pre-eminent for many years, the US is nevertheless a scientific superpower in relative decline. Japan, Germany, the UK, and France (in the purple circle) have maintained their positions in the first tier of nano countries, albeit with declining ranks due to the rise of China.

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[34] In this article, a whole counting method is adopted to accredit publications to countries and affiliations. For example, in the case of a nano paper with four co-authors reporting two US affiliations and one Chinese affiliation, in counting authorship at the country level, the US and China will each be counted only once. In terms of counting authorship at the organization level, in the above case, each *unique* affiliation will also be counted once.

Table 3.1: Ranking of Countries by Nanotechnology Publication Counts

Rank	1990-1995	1996-2000	2001-2006
	Country (Global Share)	Country (Global Share %)	Country (Global Share %)
1	USA (38.3%)	USA (27.9%)	USA (26.5%)
2	Japan (11.8%)	Japan (14.4%)	China (15.2%)
3	Germany (10.3%)	Germany (12.2%)	Japan (12.0%)
4	UK (7.9%)	China (7.7%)	Germany (9.7%)
5	France (7.7%)	France (7.7%)	France (6.5%)
6	China (4.0%)	UK (7.1%)	UK (5.5%)
7	Italy (3.9%)	Russia (4.8%)	South Korea (5.0%)
8	Canada (3.9%)	Italy (3.9%)	Russia (3.8%)
9	Russia (2.7%)	South Korea (2.9%)	Italy (3.7%)
10	Switzerland (2.3%)	Canada (2.7)	India (3.1%)
	13 Spain (1.9%) 14 India (1.6%) 16 South Korea (1.2%)	12 Spain (2.6%) 13 Switzerland (2.3%) 14 India (2.0%)	12 Spain (2.8%) 14 Canada (2.6%) 15 Switzerland (1.7%)

<u>Internal Driven Quantitative Growth</u>

In the study period from 1990 to 2006, China had been involved in 43,767 peer-reviewed journal articles indexed in WoS. With its exponentially increasing participation in total nanotechnology publications, China is now the second largest producer annually. Its number of internationally co-authored collaborations, however, demonstrated only linear growth. As shown in Figure 3.1, the share of China's internationally collaborated nano articles relative to its total nano papers remained stable during the entire time period. Interestingly, when benchmarking against China's total number of publications in all disciplines, the share of those with collaborators in nanotechnology was consistently lower than that with collaborators in all research fields. This suggested the importance of *domestic* activity in China's nanotechnology research output. A further explanation may be that nanotechnology is, or at least some specific fields in nanotechnology are, heavily dependent upon military funding, which makes it unlike other fields traditionally inviting international cooperation and collaboration (Hamblin, 2000).

At first glance, this finding somewhat contradicted earlier findings that showed an increasing proportion of internationally collaborated papers for many countries, particularly considering the existence of Chinese Diaspora. On second thought, however, this observation was explicable. Firstly, given its massive number of scientists, China has a large market for domestic collaboration. Secondly, because of the increased coverage of Chinese journals indexed in WoS (Lin & Zhang, 2007), existing research in China is becoming more visible in the international community, which also explains why the number of domestic publications has outgrown the number of internationally collaborated publications. Lastly, the phenomenon of seeming internally driven growth may also result from the fast manner in which Chinese domestic scholars absorb knowledge spillover from across national borders.

Table 3.2 lists the distribution of China's internationally collaborated nano articles sorted by the number of participating countries. Chinese scientists have co-published 7,006 nano articles with collaborators from 70 countries, including the US, Japan, and Germany. These top three "nano countries," as shown in Table 3.2, are also those countries most intensively collaborating with China, accounting for more than 50% of the total of Chinese international collaborations.

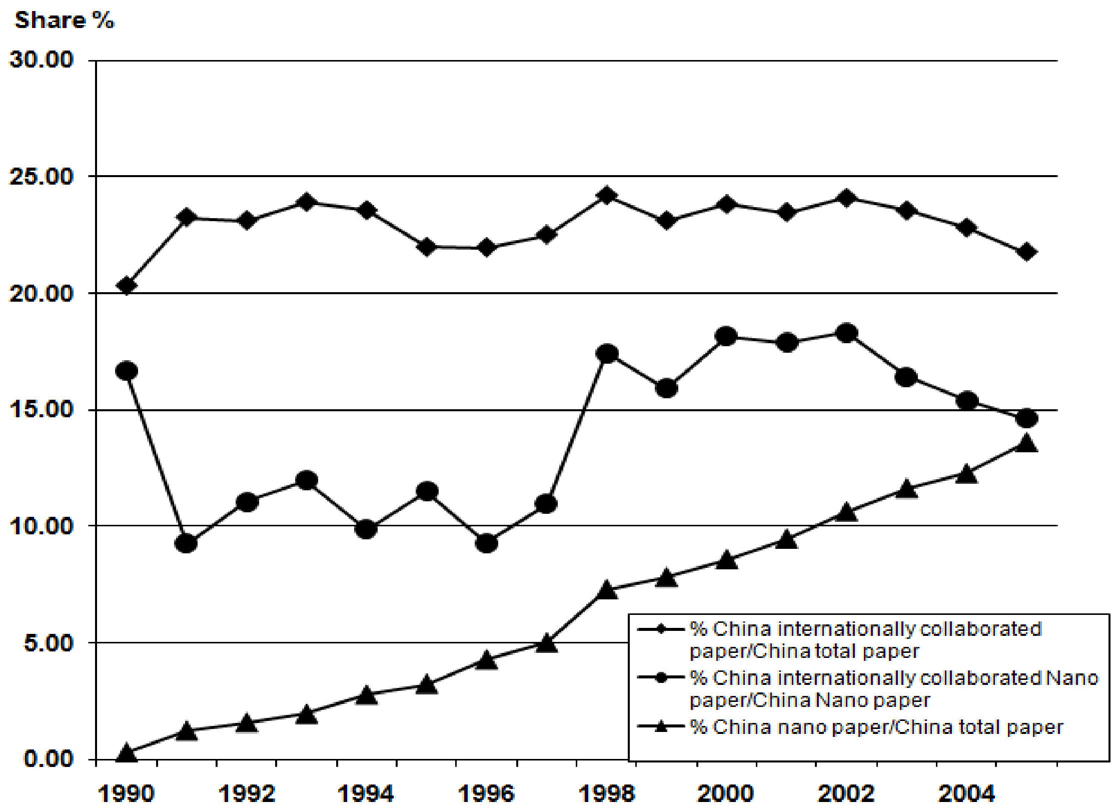

Figure 3.1 Growth of the number of Chinese nano publications: counts and shares

Note: The shares of global publications and global co-publications are calculated based on data retrieved from STN at Fraunhofer, ISI.

Table 3.2: Top 10 Countries Collaborating with China in Nanotechnology

Rank	# Records	Share	Country
1	2051	29.3%	US
2	1426	20.4%	Japan
3	792	11.3%	Germany
4	508	7.3%	Singapore
5	452	6.5%	UK
6	344	4.9%	Australia
7	329	4.7%	South Korea
8	314	4.5%	France
9	300	4.3%	Canada
10	184	2.6%	Sweden

China-US Co-publications in Nanotechnology

Quantitative & Qualitative Growth

The US is China's favorite research partner. Approximately 30% of Chinese internationally collaborated research in nanotechnology involves at least one researcher from the US. Starting from a very low base of research collaboration, Sino-US collaboration increased sharply from only 22 nanotechnology articles with co-authors from both countries during 1990–1992 to more than 1,000 in the period of during 2003–2005. When benchmarked against collaboration with the other countries, Sino-US co-authorship was notably higher than China's co-publishing efforts with the other four of China's favorite collaborating countries (Suttmeier, 2008). Figure 3.2 demonstrates the dominant role of the US in China's international collaboration.

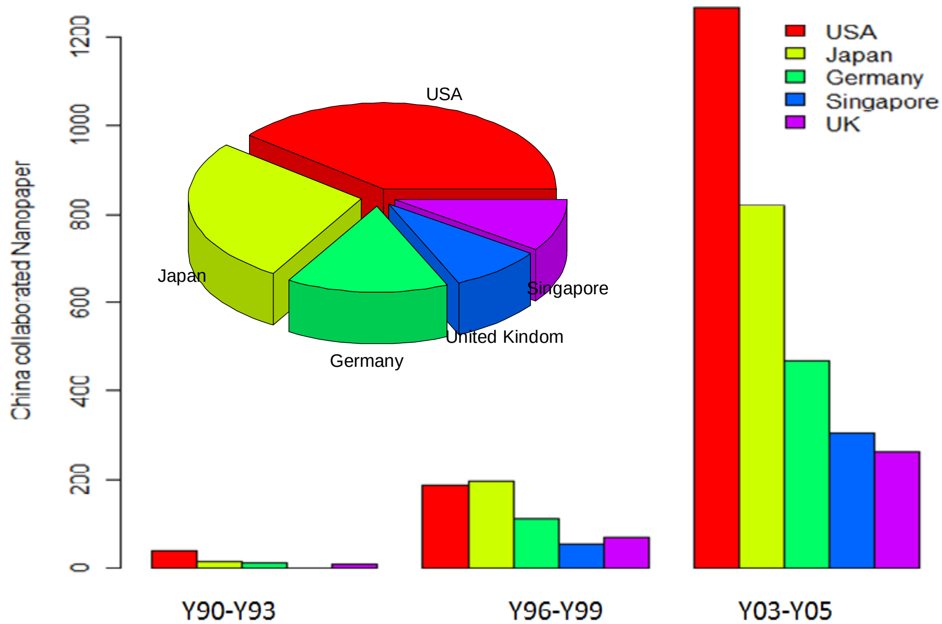

Figure 3.2 Country shares of internationally collaborated Chinese nanotechnology research

In addition to quantity, collaborative US-China nano research also populated the high end of citations of China nano research. In all of China's internationally collaborated articles, the US was involved in 56% of the 25 most cited articles, followed by Germany (16%), Japan (12%), and the others. These findings were consistent with the findings of Youtie et al. (2008), which showed that the US produced the highest quality of research as measured by citations. Considering the dynamic change of research impact, it is worth noting that the research visibility of the US-China co-published papers increased over time (Figure 3.3). Both hint that the Sino-US collaboration extends beyond quantitative growth.

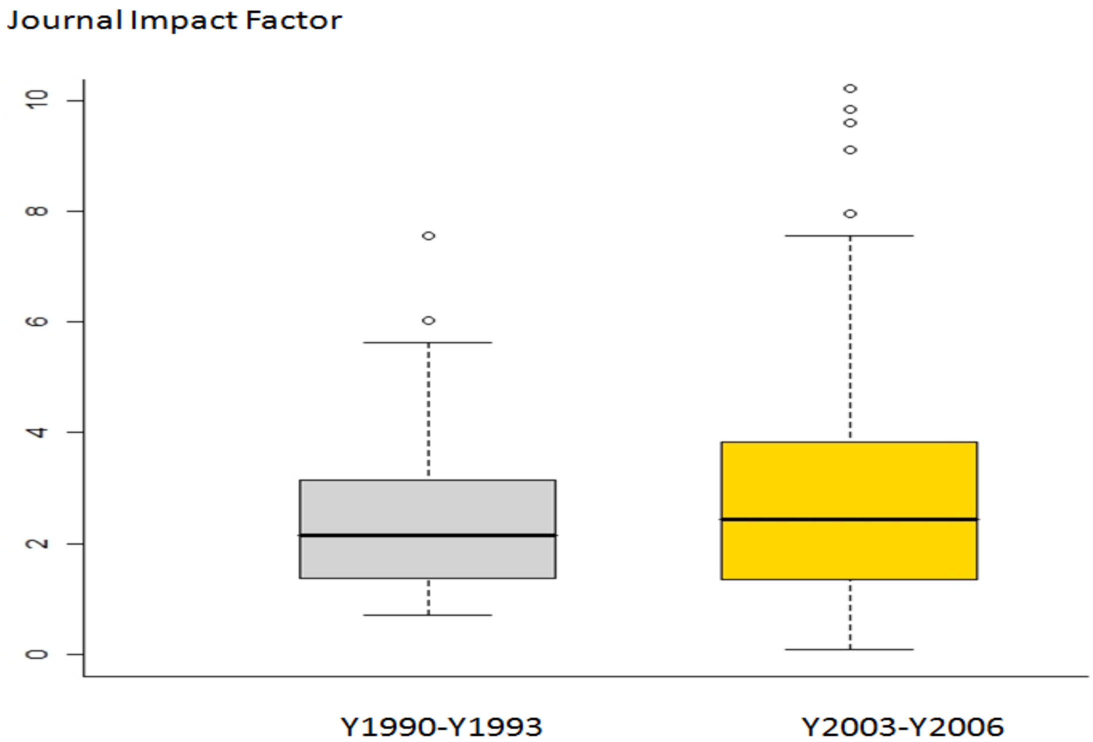

Figure 3.3 JIF distribution of US-China collaborated nano papers

<u>Collaboration Pattern: Decentralized (US) vs. Centralized (China)</u>

Although the US-China collaboration takes the lion's share of China's international joint research, as shown in Table 3.2, only one American university (Drexel University) was listed among the top 10 foreign institutes collaborating with China. This suggested that the collaborating universities in the US are decentralized (Table 3.3). By contrast, six out of ten universities from the top collaborating foreign institutes were located within Japan, which constitutes 40% of the total of Sino-Japanese co-authored articles.

Table 3.3: Top 10 International Affiliations Collaborating with China

Rank	# Records	Affiliation (Name, Country)
1	239	Natl Univ Singapore, Singapore
2	212	Nanyang Technol Univ, Singapore
3	192	Tohoku Univ, Japan
4	101	Univ Sydney, Australia
5	92	Osaka Univ, Japan
6	86	Univ Tokyo, Japan
7	86	Natl Inst Mat Sci, Japan
8	79	Drexel Univ, US
9	78	Kyoto Univ, Japan
10	77	Tokyo Inst Technol, Japan

The decentralized collaboration pattern on the US side was also supported by a comparison of collaborating partners from the US and China. Table 3.4 lists the major players involved in Chinese-US American joint research. As demonstrated, the Chinese Academy of Sciences (CAS), China's most prolific research institute, is also actively involved in cross-border collaboration. About 29% of Chinese nano articles had at least one author from CAS, and over 30% of China-US collaborative articles were affiliated with CAS institutes in our nano dataset. This proportion was even larger than the total number of China-US collaborative papers from the top ten US American institutes. Among Chinese universities, Tsinghua University and Peking University stood out in both total number of articles and internationally collaborative ones.

In terms of geographical distribution, all of the ten most prolific cities were located in eastern China, two, Changchun and Hefei, are in middle China, and none are in western China. Beijing far outperformed other cities: about 36% of Sino-US co-authored articles had at least one author from Beijing. These findings were not surprising considering the research disparity among the different regions of China. Hosting nearly one-fifth of China's science and technology staff, Beijing commanded over 30% of China's investment in R&D institutes. Not only the largest but also the most prominent research institutes are located in Beijing, including many CAS institutes and other leading universities such as Tsinghua University, Peking University, and others, which explains the highly right-skewed distribution of scientific performance. In contrast, US collaborators were distributed across a much wider geographic coverage of 49 states. These differing patterns of scientific participants in collaboration appeared to reflect the characteristics of the scientific systems in China and the US (Yamashita & Okubo, 2006).

Table 3.4: Distribution of Sino-US Co-authored Papers by Affiliations

Rank	Share	Affiliation _US	Share	Affiliation _China
1	4%	Drexel Univ	30%	Chinese Acad Sci
2	4%	Georgia Inst Technol	8%	Tsing Hua Univ
3	3%	Univ Illinois	6%	Peking Univ
4	3%	Med Coll Georgia	6%	Univ Hong Kong
5	3%	Univ Calif Berkeley	5%	Nanjing Univ
6	2%	Univ Texas	4%	Fudan Univ
7	2%	Oak Ridge Natl Lab	4%	Hong Kong Univ Sci & Technol
8	2%	Univ Michigan	3%	City Univ Hong Kong
9	2%	Univ Tennessee	3%	Jilin Univ
10	2%	Rensselaer Polytech Inst	3%	Univ Sci & Technol China

Collaboration Content

Nanotechnology is a highly interdisciplinary field. Table 3.5 shows that a subset of areas dominates in the field of nano publications in China. As indicated by subject codes assigned by Thomson Reuters, Chinese nano research spans 151 different subject categories,[35] and joint co-publications with the US fall into 108 categories. Nevertheless, the top ten account for ~80%, most of which belong to the materials sciences, physics, and chemistry domains. Comparing the top ten subject codes appearing most frequently in Chinese nano research in general and China-US joint publications, Table 3.5 indicates that the research fields in which Chinese and American

[35]Thomson Reuters provides one of 175 subject categories to each science article it collected in 2006. Source: http://admin-apps.isiknowledge.com.www.library.gatech.edu:2048/JCR/static_html/scope_notes/SCIENCE/2006/SCOPE_SCI.htm

colleagues most intensively collaborate are fields in which the Chinese have traditional strengths such as physics, material sciences, and other basic disciplines.

Dynamics of Collaboration Content

The development of research content in China-US collaborative papers broken down by years is depicted in Figure 3.4. The science overlay maps were generated utilizing the toolkit of the science overlay map developed by Rafols, Porter, and Leydesdorff (forthcoming; Rafols & Meyer, 2010). Pajek software (version 1.26) was used based on the subject categories of 2,051 collaborative nanotechnology papers co-authored by Chinese and American scientists. In order to reduce the erratic publication variation by year, the publication years were separated into three four-year phases: 1990–1993, 1996–1999, and 2003–2006. In the overlay maps, the gray and black background arcs indicate the connections among 175 subject categories (hereinafter SCs) in 2006 provided by Thomson Reuters, and the weights of arcs are related to the number of SCs for all general publications considered. The colored nodes, whose size is proportional to the number of joint China-US nano papers, are aggregated scientific disciplines based on SCs. For more detailed descriptions of the science overlay map, please refer to Porter and Youtie (2009).

Table 3.5: China Nanotechnology Publications by Disciplines: Total vs. the China-US Collaboration

China Nano Publication			The China-US Co-published Nano Articles	
Rank	**Share**	**Subject Category**	**Subject Category**	**Share**
1	24%	Materials Science, Multidisciplinary	Materials Science, Multidisciplinary	21%
2	15%	Physics, Applied	Physics, Applied	19%
3	13%	Chemistry, Physical	Physics, Condensed Matter	15%
4	13%	Physics, Condensed Matter	Chemistry, Physical	11%
5	10%	Chemistry, Multidisciplinary	Chemistry, Multidisciplinary	9%
6	9%	Polymer Science	Polymer Science	8%
7	6%	Metallurgy & Metallurgical Engineering	Physics, Multidisciplinary	5%
8	6%	Physics, Multidisciplinary	Physics, Atomic, Molecular & Chemical	4%
9	3%	Chemistry, Analytical	Metallurgy & Metallurgical Engineering	3%
10	3%	Physics, Atomic, Molecular, & Chemical	Dentistry, Oral Surgery, & Medicine	3%
	0.2%	46 Dentistry, Oral Surgery & Medicine	14 Chemistry, Analytical	2%

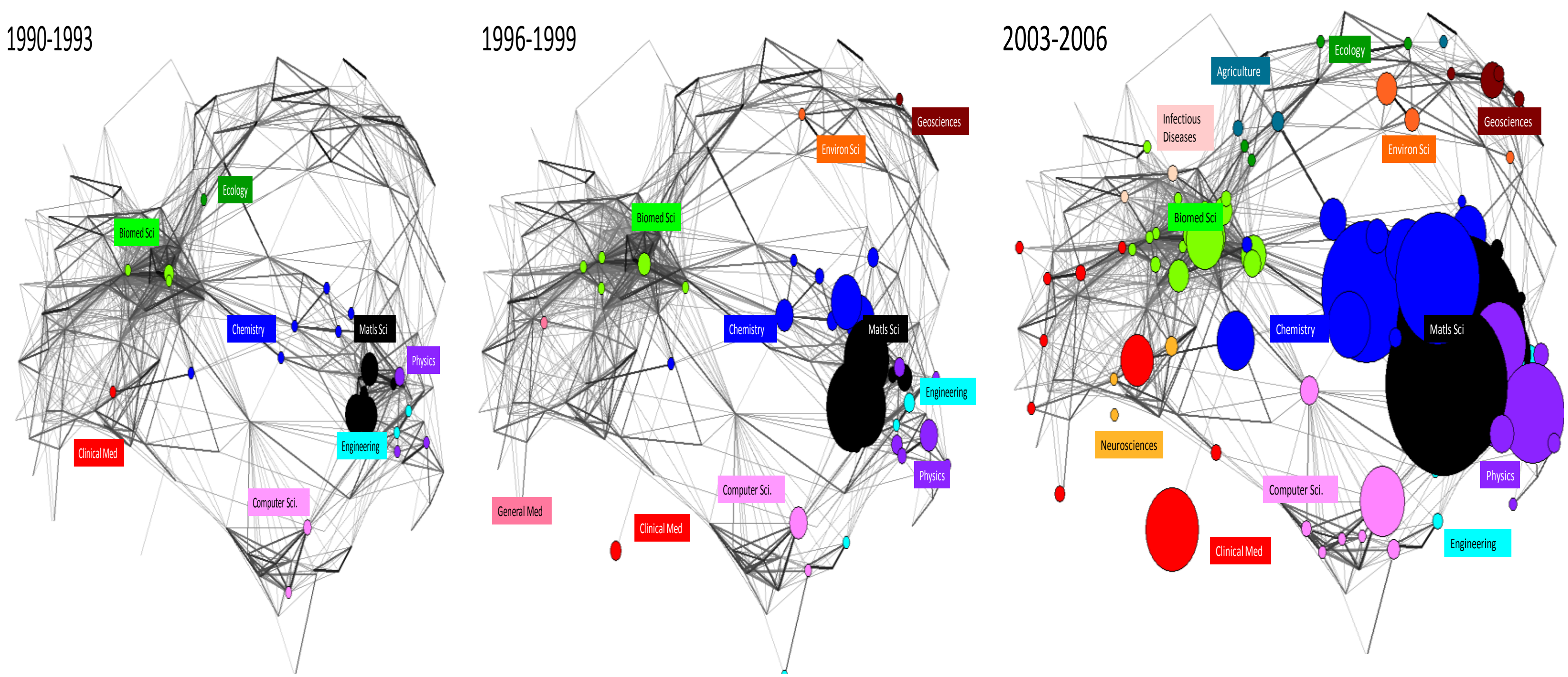

Figure 3.4 Science overlap map of China-US nano papers: three phases

These three maps present several interesting results. Not surprisingly, the network of all collaborative domains has grown in both size and complexity. During the period of 1990–1993, American and Chinese scientists co-published 185 articles in the field of nanotechnology. The eight macro-disciplines covered are materials science, physics, engineering, chemistry, ecology, biomedical sciences, and clinical medicine. During the second phase of 1996–1999, another two disciplines (geosciences and environmental sciences, or general medical) produced nanoscience and nanotechnology articles. More interactions between materials science and chemistry took place, as represented by the closer, overlapping nodes of the two fields. However, the connections among other macro fields are still rather disparate. From 2004 to 2006, collaboration between China and the US entered a period of prosperity. Not only did the variety of domains expand to the fields of ecology, agriculture, infectious diseases, and neurosciences, but the number of collaborative papers in the existing disciplines also grew dramatically. This growth was particularly marked in clinical medicine. In addition to the new collaborative domains and the burgeoning existing domains, another major change reflected by the node positions in the maps is the increasing connectedness among the different macro-disciplines. More importantly, the dynamics of China-US joint research indicated that the number of co-publications by US American and Chinese scientists is on the rise in many subject categories; however, such a trend is particularly pronounced in the fields of nano materials, nanobiology and nanomedicine, and nano electronics, which are also among the sub-domains from which we selected CKMs for further exploration. These three overlay maps together led us to conclude cautiously that a structural change of content for US-China nano collaboration is taking place.

Summary

This chapter utilized bibliometric analysis and science mapping to visualize the patterns of the US-China collaboration in nanotechnology. It showed that the explosion of nanotechnology research in China, arguably an early participant in this domain, is mainly internally driven. Collaboration between the US and China, however, plays an important role in China’s research visibility and research frontier. The increase of citations and expansion of subject categories of US-China collaborated articles suggested that it is not merely the number of papers on which China has collaborated with the US but the research visibility and coverage of collaborating content that have contributed to the rise of China in this promising field. The bibliometric analyses also found that non-elite US research universities collaborate with Chinese elite PRI and in research domains where China is traditionally strong. This, on one hand, suggested the comparatively advanced level of the US nanotechnology development over China considering the quid pro quo exchange. On the other hand, from the perspective of international R&D exploitation, the findings are relevant to policy implications for both countries, which will be discussed in Chapter 6.

CHAPTER 4

INTERNATIONAL COLLABORATION AND RESEARCH QUALITY

Introduction

The bibliometric analyses in the previous chapter showed that the number of joint publications between nanoscientists of the US and China has been growing over time, and the collaborated research fields between the two countries are expanding, too. In fact, the gap in research visibility between the nano research in the US and China is closing over the years. In 1990, the mean difference between the US and China for citations per article was 1.69; by 2009, the statistic had dropped to 0.44.[36] In light of both countries' sizable investments in nanotechnology, the existence of the Chinese Diaspora, and the growing phenomenon of reverse migration, this narrowing gap in the number of citations likely stems from unbalanced knowledge spillover due to international collaboration. However, supporting evidence for this conjecture is still lacking.

The impact of international collaboration on research performance has been explored extensively in prior research. In spite of the rich volume of literature, authors are in disagreement. Since the seminal work of Katz and Martin (1997), the amount of evidence supporting the positive *correlation* between collaboration and research performance has been accumulating. Narin, Stevens, and Whitlow (1991) found that biomedical papers with

[36]The citation figures were calculated based on the latest Georgia Tech Nanotechnology Publication Database (1990–2009) which was updated in January 2010. The mean citation for China's nano articles published in 1990 is 0.75 compared with 2.44 for the US. In 2009 the comparison changed to scores of 0.39 and 0.83 for China and the US respectively.

international co-authors have a larger impact than both single-authored and nationally co-authored papers. Bordons et al. (1996) claimed that in Spanish biomedical publications, internationally co-authored articles were of higher quality and international collaborators were more productive than their domestic counterparts. A recent study led by Barjak and Robinson (2007) demonstrated the positive impact of international collaboration on the quantity and quality of a European Union research group. Other studies reported similar findings (Persson et al., 2004; He, Geng, & Campbell-Hunt, 2009).

Conflicting evidence has been reported recently in terms of both general collaboration and collaborative research across national borders. Avkiran (1997) reported no significant difference between the quality of collaborative and individual approaches to finance research. In a comparative study, Duque et al. (2005) found that, in the context of developing countries, collaboration is not related to “any general increment in productivity.” Leimu and Koricheva (2005) found that internationally co-authored articles are not cited at a higher rate than domestically co-authored papers in the field of ecology. In another study on one large European university, Carayol and Matt (2004) reported no evidence supporting the impact of international collaboration on research productivity at the lab level. Findings in support of the trade-off effect of international collaboration on quantity and quality has also been reported. Using the panel publication data of 110 top US universities, Adams, Black, Clemmons, & Stephan (2005) argued that foreign collaboration among research institutes was positively correlated with citations but negatively correlated with productivity.

Table 4.1 summarizes the methods and results of selected studies whose findings on the effects of general scientific collaboration and international collaboration in particular were inconclusive in terms of both direction and impact on research performance.

Table 4.1:Selected Empirical Studies: Collaboration vs. Research Performance

Article	**Data Source**	**Country**	**Research Scope**	**Method**	**Unit of Analysis**	**Results**	**Collaboration level**
Narin et al., 1991	WoS	EU countries	Biomedical Papers	Descriptive	Paper	+ Quality	International collaboration
Bordons et al., 1996	WoS	Spain	Biomedical Research	Descriptive	Individual Scientist (Team Leader)	+Productivity + Quality	International collaboration
Barjak & Robinson, 2007	Survey	10 EU countries	Life Sciences	Modeling	Research Team	+ Productivity + Quality	International collaboration
Persson et al., 2004	WoS	Global	All Fields	Descriptive	Paper	+ Quality	General collaboration
He et al., 2009	WoS	France	Biomedical Research	Modeling	Individual Scientist	+Productivity + Quality	International collaboration
Leimu and Koricheva, 2005	Oecologia	EU and US	Ecology	Modeling	Individual Scientist	Not correlated with quality	International collaboration
Glanzel & Schubert, 2001	WoS	Global	Chemistry	Descriptive	Paper	+ Quality	International collaboration
Duque et al., 2005	Survey	Less developed areas (Ghana, Kenya, and the south-western India)	All Fields	Modeling	Individual Scientist	Not correlated with productivity	General collaboration
Adams et al., 2005	WoS	USA	12 Selected Research Fields	Modeling	University Department	- Productivity + Quality	General collaboration
Carayol & Matt, 2004	University administrative reports	France	All Fields	Modeling	Lab Level	Not correlated with productivity	International collaboration

Prior research, while insightful, suffers from three interrelated, mutually influencing drawbacks. One is the ignorance of self-selection when individual heterogeneity is not controlled for in most studies. If the saying “birds of a feather flock together” has any validity, then higher research performance, meaning more publications and greater citations, do not necessarily result from collaboration. Secondly, but on a related note, many studies focus on only aggregate-level analysis rather than individual-level analysis. Among those studies adopting micro-level analysis, the omission of variables in model specification is problematic. As noted by Garfield, the founding father of Thomson Scientific, a citation itself is a function of many other variables in addition to scientific quality (Garfield, 1972; Bornmann, Mutz, Neuhaus, & Daniel, 2008). It is for this very reason that more recent studies have begun to adopt statistical modeling to exclude competing explanations. Unfortunately, important variables such as language and size of the originating scientific communities are still missing. The third problem is that many studies have adopted cross-sectional data rather than dynamic longitudinal data. The few that have adopted longitudinal data have all assumed a constant impact of collaboration over the years, which is highly inconsistent with insights into absorptive learning and knowledge accumulation.

As illustrated in Table 4.1, in addition to various disciplines, the studied country context seems also related to the mixed results pertaining to collaboration. In the case of China, while the role of international collaboration in scientific development is widely assumed (Jin et al., 2008; Appelbaum, 2007; Suttmeier, 2008), empirical evidence of such collaboration remains sparse. Therefore, to augment the literature, this chapter refers to data obtained from Chinese nano publication data, a panel publication of CKM and their curricula vita (CVs) to explore the impact of China-US collaboration on the research quality of Chinese nanoscientists.

Hypotheses

Built upon past studies and the descriptive statistics in Chapter 2, the first hypothesis follows:

H1: *International collaboration has a positive impact on the quality of China's nanotechnology research.*

During the period of 1990 to 2006, Chinese scholars collaborated with 70 countries in the field of nanotechnology and co-published 7,000 papers. In addition to collaborating with US American researchers, Chinese researchers also collaborated extensively with their Asian and European counterparts.

Given that the US has been the number one knowledge producer in nanotechnology, I further hypothesized the following:

H2: *Research collaboration with US researchers has a larger positive impact on the quality of research in China than other international collaboration without US researchers.*

Given the highly-skewed distribution of publication quantity and citation (Moed, 2005; Stephan, 1996), the selection of Chinese knowledge moderators (CKMs) suggests that nano papers with contributions from CKMs receive a higher number of citations than the average. This led to the third hypothesis:

H3: *With other variables remaining constant, articles written by CKMs are more likely to evidence higher quality than research conducted without CKMs.*

The above three hypotheses tested the impact of international collaboration on research quality under a strong assumption of a constant effect over the years. However, it was reasonable to assume that the accumulation of knowledge and collaborative experiences over time have enhanced Chinese researchers' absorptive capacity. That is, comparatively, the benefits from international collaboration relative to non-international collaborative research decrease over time, leading to the fourth hypothesis:

H4: *The impact of US-China collaboration on China's nano research quality diminishes over time with less impact in more recent years.*

Hypothesis 4 relaxed the assumption of a constant effect of international collaboration by allowing it to vary over time. To test this hypothesis, interaction terms between international collaboration and publication year were included in the estimation model, and the impact dynamics could be identified by the signs of the interaction term. So if the impact of collaborating with US nanoscientists demonstrated a time-decay pattern, the interaction term-the expected *difference* of *increased* quality of US-China collaborated papers against Chinese domestic papers by each additional year-would show a positive sign.[37] In other words, the increased journal impact factor (JIF) is larger for CKM's domestic papers than the increase for CKM papers involving US scholars.

The next hypothesis considered the heterogeneity of CKMs in terms of their connection with the US and China and the problem of panel attrition simultaneously. As disclosed in the previous chapter, a majority of CKMs were found to have visited the US and/or had gained work experience with US affiliations for varying periods of time. It was reasonable to presume that scientists who have worked in an institute for a certain period of time are likely to have been exposed to and thus influenced by the research there (Louis, Holdsworth, Anderson, &

[37] This is due to the coding of publication time: more recent years have smaller value.

Campbell, 2007). Since longer stays of Chinese scholars suggest closer proximity and thus more social and intellectual interaction (social capital) with US researchers, this led to the fifth hypothesis:

H5: *Chinese scholars who have worked in US institutions are more likely to have co-authored papers with American scholars than Chinese visiting scholars who are sponsored by the Chinese government.*

Variables

To test the above hypotheses, this research utilized two publication databases. The full dataset, pooled cross-sectional data, included all nano articles reporting at least one Chinese affiliation published in the years 1990 to 2006. The limited dataset was a panel data set of 77 CKM nanotechnology publications from these years. All of the hypotheses except for H3 (which can only be examined in the full dataset) were tested in both the full and panel datasets.

The unit of analysis was a nanotechnology research article published in a peer-reviewed international journal. The *dependent variable* of research quality[38] was measured by two citation-based indicators: the journal impact factor, denoted by *JIF*, and the number of citations received, denoted as *CITATIONS.*

Journal Impact Factor

The JIF is a proxy indicator of the importance of journals, indicated by the *average* number of citations that an article in that journal received. According to Thomson Reuters, it is calculated by dividing the number of current citations to articles and reviews published in the

[38]This term *research quality* has been used interchangeably with the term *research impact* in some previous studies.

two previous years by the total number of articles and reviews published in the same two years.[39] In general, articles published in a journal with higher JIF suggest greater visibility.

Given its formula, the impact factor of each journal may change from year to year. A plotting of the JIF of the top five journals that published nano research (Figure 4.1), however, shows no significant differences among JIFs over the period of 2000 to 2006.[40] Thus due to data availability, the 2005 JIF was used as a proxy indicator that captures the quality of an academic journal. To ensure data consistency, the analysis excluded journals that did not have a reported 2005 JIF (such as new journals established after 2005). This left 41,487 in the full dataset and 2,186 in the CKM panel dataset. The descriptive statistics showed that the mean JIF of Chinese nano papers was 1.4 with a standard deviation of 1.78. On average 50% of papers were published in journals with an impact factor above 1, about 25% were accepted by journals with an impact factor greater than 2, while 10% were accepted by journals with a JIF greater than 3.

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[39]The definition and formula of the JIF is available at http://www.thomsonreuters.com/business_units/scientific/free/essays/impactfactor/

[40]The 2000–2006 JIFs of ISI indexed journals were compiled during my visit in Fraunhofer ISI, Karlsruhe.

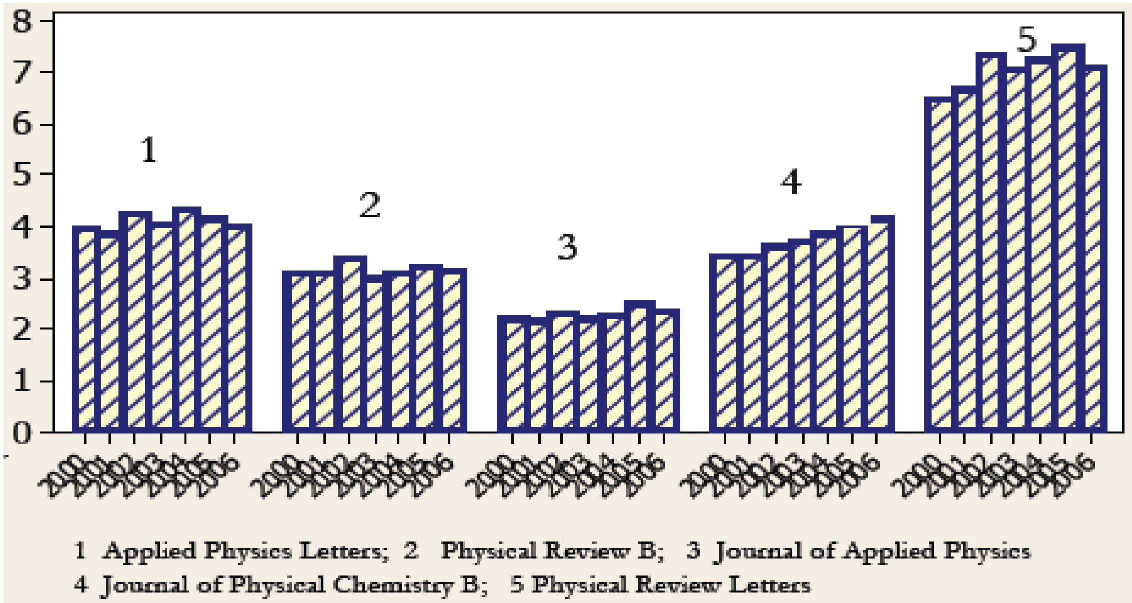

Figure 4.1 Changes in the impact factors of selected journals (2000–2006)

Note: The data were compiled based on ISI journal citation reports ranging from 2000 to 2006.

CITATIONS

The distribution of citations within the same journal, however, was highly skewed (Moed, 2005). This leads to the second indicator of research quality: accumulative citations to an article created virtually after its publication. Similar to JIF, a higher number of citations indicates higher quality. In our database, the mean yearly citation rate for Chinese nano papers was 4.4, ranging from 0 to 753. However, about two-fifths of the Chinese articles had not yet been cited as of June 2006 when the data was downloaded.

In addition to the JIF and the summed citations, another common practice of measuring research quality is using an n-year citation window with n typically 3 or 5. This method has been adopted in previous studies (Persson, Glanzel, & Danell, 2004; Glanzel & Schubert, 2001; Adams et al., 2005; Glanzel & Schoepflin, 1995). This study, however, did not adopt this method for three reasons. The first was a practical issue: downloading nano publications did not produce immediate results or calculate the n-year citation count for each article. However, the total number of citations without dates of citation was available. Secondly, the proper cut-off point of citations varies significantly according to the research area (Rinia et al., 2001). Given the multidisciplinary nature of nanotechnology, a single cut-off point for a citation is arbitrary. Although the probability of a research paper being cited falls off sharply after a certain number of years, citations with long lag times occur (Glanzel, 2008). Last but not least, nanotechnology is still a nascent technology. If this study had used, for example, a three-year citation window, only articles published during the years 1990 through 2003 would be available for citation analysis. This investigation would have excluded studies from the latest "boom" years. Not surprisingly, the use of both the JIF and the citation number as indicators of research quality also poses limitations and caveats. Accepting their inherent limitations for now, I attempted to examine both *JIF* and *CITATIONS* as dependent variables.

Explanatory Variables

International collaboration: Three dummy variables were generated based on whether or not and where a non-Chinese researcher was involved in the process of knowledge creation. If an article reported affiliations in two or more countries, the variable of *ICOLLAB* was coded as 1; if it reported only Chinese affiliation(s), it was coded as 0. Since this study focused on China-US collaboration, the study further separated *ICOLLAB* into another two dummy variables: *USCOLLAB if* an American affiliation was reported in an international collaboration; and *NUSCOLLAB* if it was not.

Knowledge moderation: As noted earlier, the positive *correlation* between internationally co-authored papers and *JIF/CITATIONS* in cross-sectional data suffers from "reverse causality and survivor bias" (Fleming, Mingo, & Chen, 2007). The causal effect requires that the left side variable, namely *JIF/CITATIONS*, an indicator of a good researcher, is the *result* of the right side variable *ICOLLAB*. The presumed logic here is that international collaboration produces a "good paper" that is cited more often than other papers. The factor of more citations, no doubt, further promotes the author's reputation. Possible reverse causality, however, is that the denotation of a "good scholar," which is often measured by a higher number of *JIF/CITATIONS*, increases the probability that these scholars will be designated a *COLLAB* over others. Given the definition and operationalization of CKM, it would not be surprising to find that the average number of citations of CKM-related articles is higher than that of non-CKM-related articles (APPENDIX C.1). Two possible explanations can account for such observations. Good researchers produce high quality papers, which leads to high citation rates, or the boundary-spanning position produces novel ideas, which are then cited widely. To distinguish this person versus position argument, two variables were created to test the knowledge moderation effect: *KMOD* indicated whether the article involved any CKM or not. This variable *KMOD* was included in the testing of the full dataset. Further, *AFTKMOD* stood for CKM panel regression. The variable *AFTKMOD* was coded as 1 if the CKM article was published after or in the same year of the CKM's second internationally collaborated article, assuming that the repeated collaboration provides CKMs with baseline knowledge and skills necessary to absorb and further transfer to other collaborators (Cohen & Levinthal, 1990).

<u>Proximity to the US</u>: Based on the CVs of the CKMs, a set of dummy variables that capture different types of connections with US research institutes was constructed. If a CKM had established a formal relationship with a US affiliation—either working in a position (including a post-doc position) or completing a doctorate degree in the US, the variable *USWRK* was coded as 1; if the CKM had been a visiting scholar in a US institute, the variable *USVST* was coded as 1; and if neither was the case, the third dummy variable *USOTH* was coded as 1.

<u>Proximity to China</u>: Similarly, another three dummy variables were generated to capture the connection of CKMs with Chinese research institutes. The variable *CNWRK* was coded as 1 if the CKM had established a formal association with a Chinese affiliation; *CNPRM* was coded as 1 if a CKM was currently not in China but was connected with a Chinese affiliation via some prestigious program such as the *Hundred Talents Program,* the *Thousand Talents Program*,

Yangtze River Scholars, and so forth; and the third dummy variable *CNOTH* was coded as 1 if neither was the case.

Control Variables

To eliminate competing explanations, the model included the following five sets of *control variables*:

<u>Language</u>: Past studies have found that SCI coverage does not favor non-English research output. This language bias phenomenon may lead to inaccurate conclusions about research productivity when we compare SCI-indexed articles across nations given the lack of Japanese, German, and French journals (Lin & Zhang, 2007; van Leeuwen et al., 2001). Except for coverage bias, language also matters in terms of research visibility of all articles indexed in the WoS. Academic journals are important sources of communication within the scientific community. One prerequisite for such scholarly communication is readability. Intuitively few researchers would cite scholarly work that they found difficult to comprehend. Although the number of indirect citations is increasing, articles written in English are more likely to be cited than others. In the past, this factor was probably disregarded because of the commonly acknowledged, even accepted, bias toward English journals in the WoS. However, this situation is changing, so controlling for language is especially critical since the number of nanotechnology publications in the WoS written in Chinese has increased sharply (Lin & Zhang, 2007).

<u>Scope of research collaboration</u>: One methodological issue marring the validity of using citation as an indicator of research quality is self-citation, meaning citations by an author to his/her previous work (Van Raan, 1998; Wallin, 2005). It is too costly in time and computational complexity to remove self-citations from about 43,000 publications. I compromised by controlling for research collaboration scope since multi-authored articles have a higher probability of being cited by author themselves (Glanzel & Thijs, 2004; Katz & Hicks, 1997). These three variables indicating collaboration scope are number of authors, number of institutions, and number of countries reported in the byline of articles. Some studies found that

they are positively correlated with the number of citations (Goldfinch, Dale, & DeRouen, 2003; Lawani, 1986; Baldi, 1998). However, other studies suggest the opposite (Ventura & Mombru, 2006; Seglen & Aksnes, 2000). Thus, this work included these variables in the model without prior expectations as to the direction of influence.

Researcher capacity: In addition to CKMs, another factor that may influence citation is the quality of CKMs' Chinese collaborator(s). As discussed in Chapter 3, unlike US researchers, the best Chinese researchers are concentrated within a few elite universities and research institutes. In Mainland China, the Chinese Academy of Sciences (CAS) and elite Chinese universities (APPENDIX C.2) have traditionally attracted the best researchers and students who form and maintain extensive international collaborations with their counterparts overseas. For historical reasons, Hong Kong, with its English-speaking tradition, has formed close research exchange activities with developed western countries. To reduce the possible self-selection effect of co-authors, three dummy variables—*CAS*, *ELITE-UNIV*, and *HONG KONG*—were included in the models.

Research discipline: Another factor that influences the number of citations is research discipline. As observed by Moed and Van Leeuwen (1995) observed both "composition of the contents" and the characteristics of the research field influence citation as well as JIFs. For example, compared with papers in bioengineering, those in materials science may exhibit different citation patterns, directly influencing the JIF and number of citations. In fact, prior studies have found that some fields are "more amenable to scholarly interaction than other fields" (Piette & Ross, 1992; Laband & Tollison, 2000). Papers published in biomedicine are usually published in journals with larger impact factors. Differences in the impact factor due to the size of the scientific community are important for an interdisciplinary field such as nanotechnology. This research controlled for this factor by adopting the Fraunhofer ISI classification method, which differentiates nanotechnology research into 24 research fields based on subject categories.[41]

Research experience: Based on the CVs of the CKMs, a numerical variable RES-EXP was constructed to indicate research experience of researchers. The value of RES-EXP was calculated by subtracting the year in which the CKM obtained his highest degree from 2009. This variable was only used in the selection model of testing hypothesis 5.

Publication age: Publication date also influences citation-based indicators. Given their longer existence, articles published earlier are more likely to be found and cited than later papers of the same quality. In this article, elapsed time since publication was used to control for time period variations.

Table 4.2 links the variables with the testing hypotheses. Detailed descriptions of the above variables and coding mechanisms are summarized in Table 4.3. Tables 4.4 to 4.7 provide descriptive statistics for the full dataset and the panel dataset.

[41] The categorizing method of the Fraunhofer ISI initially targeted *all* articles included in the SCI-WoS. Applying it to our nanotechnology dataset, I found that 24 out of 26 research fields were covered in Chinese nano publications, indicating the multidisciplinary nature of nanotechnology.

Table 4.2: Hypotheses and Testing Variables

Variables
USCOLLAB
NUS COLLAB
KMOD
AFTKMOD
*US COLLAB*PUB_AGE*
*NUS COLLAB*PUB_AGE*
*KMOD * PUB-AGE*
*AFTKMOD * PUB-AGE*
USWRK
USVST
*USOTH**
CNWRK
CNPRM
*CNOTH **
AFFILIATIONS
PRC-CITY
AUTHORS
COUNTRIES
HONG KONG
CAS
ELITE-UNIV
CHINESE
SUBJECT
PUB-AGE

Hypotheses
H1: International collaboration
H2: US-China collaboration vs. Non-US Internationalo collaboration
H3: Knowledge moderation
H4: Time dynamics
H5: Proximity with the US institutes

Table 4.3: Description of the Variables

Type	Construct	Variable Name	Expected Direction	Description
D	Research quality/ visibility	*JIF*		Journal impact factor, 2005
		CITATIONS		Times cited since publication
I	International collaboration	*ICOLLAB*	(+)	At least one author with an affiliation outside China = 1; otherwise = 0
		USCOLLAB	(+)	At least one author with an US affiliation outside China = 1; otherwise = 0
		NUSCOLLAB	(+)	At least one non-American affiliation outside China is reported =1; otherwise = 0
	Knowledge moderation	*KMOD*	(+)	At least one Chinese knowledge moderator is involved = 1; otherwise = 0
		AFTKMOD	(+)	CKM article that was published after or in the same year as CKM's second internationally collaborated paper =1; otherwise=0
	Proximity to the US	*USWRK*	(+)	The CKM has formally associated with a US affiliation before, either working there (including postdoc) or having completed his/her doctoral study there =1; otherwise = 0
		USVST	(+)	The CKM has been a visiting scholar in a US institute =1; otherwise = 0
		*USOTH**		The CKM has never visited the US nor worked or studied there =1; otherwise = 0
	Proximity to China	*CNWRK*	(+)	The CKM has formally associated with a Chinese affiliation; otherwise = 0
		CNPRM	(+)	The CKM was currently not in China but connected with a Chinese affiliation via a prestigious national program; otherwise = 0
		*CNOTH**		The CKM has never worked in China before, is not connected via a prestigious program =1; otherwise = 0

Table 4.3 Continued

C	Scope of research collaboration	*AFFILIATIONS*	(+/-)	Number of affiliations associated with co-authorship
		PRC-CITY	(+/-)	Number of Chinese cities associated with co-authorship
		AUTHORS	(+/-)	Number of co-authors
		COUNTRIES	(+/-)	Number of co-authors' countries of affiliation
	Capacity of researcher	*HONG KONG*	(+)	Article has one or more authors from Hong Kong = 1; otherwise = 0
		CAS	(+)	Article has one author from the Chinese Academy of Sciences = 1; otherwise = 0
		ELITE-UNIV	(+)	Article has one author from one of the top 10 Chinese universities = 1; otherwise = 0
	Language	CHINESE	(-)	Written in Chinese = 1; other = 0
	Research discipline	*SUBJECT*	(+/-)	F1-F26: A set of subject dummies indicating the sub-field of nanotechnology—26 subject categories based on keywords of subject codes from Thomson Reuters
	Time	*PUB-AGE*	(+/-)	Pub_age=2006–publication year
	Research Experience	*RES-EXP*	(+/-)	Years of research experience

Note: Variable type: D = Dependent; I = Independent; C = Control.

*In the regression, *USOTH* is the reference group for the nominal variable of connection with the US while *CNOTH* is the reference group for the nominal variable of connection with China.

Table 4.4: Summary of Descriptive Statistics: Full Data

Construct	Variable	Observation	Mean	S.E.	Min	Max
Quality of research	*JIF*	41487	1.41	1.78	0	30[42]
	CITATIONS	41487	4.44	12.35	0	753
International collaboration	*ICOLLAB*	41487	0.16	0.37	0	1
	USCOLLAB	41487	0.05	0.21	0	1
	NUSCOLLAB	41487	0.11	0.31	0	1
Knowledge moderation	*KMOD*	41487	0.05	0.22	0	1
Scope of research collaboration	*AUTHORS*	41487	4.72	1.97	1	14
	AFFILIATIONS	41487	1.57	0.78	1	9
	PRC-CITY	41487	1.24	0.49	1	5
	COUNTRIES	41487	1.18	0.44	1	7
Capacity of researcher	*HONG KONG*	41487	0.08	0.27	0	1
	CAS	41487	0.29	0.45	0	1
	ELITE-UNIV	41487	0.36	0.48	0	1
Language	*CHINESE*	41487	0.14	0.35	0	1
Time	*PUB-AGE*	41487	3.30	2.87	0	15

As indicated in the correlation matrix (Tables 4.7 and 4.8), the number of collaborating countries (*COUNTRIES*) is highly correlated with the international collaboration variable (*ICOLLAB*)[43] andthus *COUNTRIES* is dropped from the models in an effort to eliminate multicollinearity.

[42] In the regression only an integer part of JIF is used.

[43] Pearson's "r" of the number of countries and international collaboration in both full and CKM panel data are 0.93 and 0.94 respectively.

Table 4.5: Summary of Descriptive Statistics: Panel Data

Construct	Variable	Observation	Mean	S.E	Min	Max
Quality of research	*JIF*	2186	2.11	2.51	0	30
	CITATIONS	2186	7.44	21.53	0	753
International collaboration	*ICOLLAB*	2186	0.29	0.45	0	1
	USCOLLAB	2186	0.23	0.42	0	1
	NUSCOLLAB	2186	0.06	0.23	0	1
Knowledge moderation	*AFTKMOD*	2186	0.83	0.39	0	1
Connection with the US	*USWRK*	2186	0.41	0.49	0	1
	USVST	2186	0.33	0.47	0	1
	*USOTH**	2186	1.16	0.80	0	2
Connection with China	*CNWRK*	2186	0.96	0.20	0	1
	CNPRM	2186	0.01	0.11	0	1
	*CNOTH**	2186	0.03	0.17	0	1
Scope of research collaboration	*AUTHORS*	2186	5.28	1.96	1	14
	AFFILIATIONS	2186	1.75	0.89	1	7
	PRC-CITY	2186	1.24	0.50	1	4
	COUNTRIES	2186	1.31	0.51	1	4
Capacity of researcher	*HONG KONG*	2186	0.04	0.21	0	1
	CAS	2186	0.42	0.49	0	1
	ELITE-UNIV	2186	0.43	0.50	0	1
Language	*CHINESE*	2186	0.07	0.25	0	1
Research experience	*RES-EXP*	2186	15.0	9.94	1	51
Time	*PUB-AGE*	2186	3.11	2.45	0	15

Table 4.6: Correlation Matrix: Full Dataset

	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	*JIF*	1.00														
2	*CITATIONS*	0.37	1.00													
3	*ICOLLAB*	0.15	0.08	1.00												
4	*USCOLLAB*	0.13	0.07	0.51	1.00											
5	*NUSCOLLAB*	0.08	0.04	0.82	-0.08	1.00										
6	*KMOD*	0.09	0.06	0.09	0.21	-0.04	1.00									
7	*AUTHORS*	0.12	0.05	0.11	0.08	0.08	0.07	1.00								
8	*AFFILIATIONS*	0.09	0.03	0.55	0.34	0.41	0.05	0.25	1.00							
9	*PRC-CITY*	-0.02	-0.03	-0.09	-0.03	-0.08	0.00	0.11	0.50	1.00						
10	*COUNTRIES*	0.15	0.08	0.93	0.50	0.74	0.07	0.15	0.60	-0.09	1.00					
11	*HONG KONG*	0.11	0.08	0.04	0.06	0.01	-0.03	-0.01	0.13	0.16	0.06	1.00				
12	*CAS*	0.07	0.03	0.00	0.01	-0.01	0.06	0.14	0.10	0.13	0.00	-0.10	1.00			
13	*ELITE-UNIV*	0.05	0.03	-0.04	-0.01	-0.04	0.04	0.04	0.06	0.06	-0.04	-0.12	-0.29	1.00		
14	*CHINESE*	-0.29	-0.10	-0.13	-0.07	-0.10	-0.05	-0.05	-0.06	0.02	-0.12	-0.10	-0.04	-0.04	1.00	
15	*PUB-AGE*	-0.06	0.26	0.00	-0.01	0.01	-0.02	-0.01	-0.03	-0.04	-0.01	0.04	0.08	0.02	-0.04	1.00

Table 4.7: Correlation Matrix: CKM Panel Data

	Variable	1	2	3	4	5	6	7	8	9	10	11
1	*JIF*	1.00										
2	*CITATIONS*	0.36	1.00									
3	*ICOLLAB*	0.19	0.03	1.00								
4	*USCOLLAB*	0.18	0.00	0.87	1.00							
5	*NUSCOLLAB*	0.04	0.05	0.38	-0.13	1.00						
6	*USWRK*	0.07	0.03	0.07	0.13	-0.10	1.00					
7	*USVST*	-0.04	0.03	-0.05	-0.11	0.11	-0.59	1.00				
8	*USOTH*	-0.03	-0.07	-0.03	-0.03	0.00	-0.49	-0.42	1.00			
9	*CNWRK*	-0.06	0.02	-0.22	-0.25	0.04	-0.25	0.15	0.12	1.00		
10	*CNPRM*	0.03	-0.01	0.12	0.14	-0.03	0.13	-0.08	-0.06	-0.54	1.00	
11	*CNOTH*	0.06	-0.02	0.18	0.21	-0.03	0.21	-0.12	-0.10	-0.83	-0.02	1.00
12	*AUTHORS*	0.10	0.01	0.10	0.07	0.06	0.05	-0.16	0.11	-0.05	0.06	0.02
13	*AFFILIATIONS*	0.14	0.00	0.62	0.56	0.20	-0.01	-0.01	0.02	-0.22	0.07	0.21
14	*PRC-CITY*	-0.05	-0.05	-0.03	0.00	-0.06	-0.05	0.08	-0.03	-0.06	0.00	0.08
15	*COUNTRIES*	0.20	0.04	0.96	0.84	0.35	0.09	-0.06	-0.04	-0.25	0.11	0.22
16	*HONG KONG*	-0.02	-0.02	0.01	0.03	-0.05	-0.05	-0.06	0.12	0.04	-0.02	-0.03
17	*CAS*	0.06	0.00	0.01	-0.03	0.08	-0.18	-0.02	0.22	-0.01	0.02	0.00
18	*ELITE-UNIV*	-0.01	0.02	-0.05	-0.04	-0.04	0.02	0.04	-0.06	0.01	-0.01	0.00
19	*CHINESE*	-0.22	-0.07	-0.11	-0.09	-0.06	-0.02	-0.02	0.04	-0.07	0.05	0.05
20	*PUB-AGE*	-0.08	0.26	-0.11	-0.16	0.08	0.02	0.05	-0.08	0.02	-0.04	0.00
21	*RES-EXP*	-0.03	0.02	0.08	0.07	0.04	-0.20	0.36	-0.16	0.06	0.01	-0.08
22	*AFTKMOD*	0.07	-0.11	0.18	0.17	0.05	-0.11	0.08	0.08	0.03	-0.05	0.05

	Variable	12	13	14	15	16	17	18	19	20	21	22
12	*AUTHORS*	1.00										
13	*AFFILIATIONS*	0.27	1.00									
14	*PRC-CITY*	0.13	0.46	1.00								
15	*COUNTRIES*	0.13	0.66	-0.04	1.00							
16	*HONG KONG*	0.01	0.10	0.20	0.00	1.00						
17	*CAS*	0.26	0.12	0.11	0.00	-0.06	1.00					
18	*ELITE-UNIV*	-0.10	0.05	0.11	-0.05	-0.10	-0.50	1.00				
19	*CHINESE*	-0.01	0.02	0.10	-0.11	0.02	-0.03	-0.02	1.00			
20	*PUB-AGE*	-0.06	-0.09	-0.04	-0.10	0.01	-0.06	0.14	-0.03	1.00		
21	*RES-EXP*	-0.10	0.10	0.12	0.07	-0.03	-0.08	0.14	-0.01	0.12	1.00	
22	*AFTKMOD*	0.05	0.09	-0.03	0.18	-0.12	0.04	-0.05	-0.08	-0.46	0.12	1.00

Models and Estimation Results

This study used STATA version 9.0 for estimation. The regression results are shown in Table 4.8 for the journal impact factor (*JIF*) and Table 4.9 for the number of citations (*CITATIONS*). The F statistics show that all the models were statistically significant.

Journal Impact Factor

Full Dataset

Panel 1 in Table 4.8 lists the estimation results using a full dataset of Chinese nanotechnology papers, that is, cross-sectional data. Model 1 reports the results of testing the impact of international collaboration and China-US collaboration on research quality (H1 and H2). Model 2 lists the results including knowledge moderation (*KMOD*) and its interaction term with elapsed time since publication (*KMOD* PUB-AGE*). Given the distribution of dependent variables, both models adopted negative binomial estimation, which is typically considered a better choice than Poisson in the case of over-dispersion.[44]

Column 1 shows that the regression coefficients of *USCOLLAB* and *NUSCULLSB* were positive and statistically significant, indicating that the average JIF of internationally collaborative articles is higher than that of the reference group—domestic Chinese papers. The coefficient of *USCOLLAB* (0.55) was nearly twice as large as that of *NUSCOLLAB* (0.28), suggesting that China-US collaboration has a larger positive impact than international collaboration without a US affiliation. The numbers of both affiliations and cities involved in collaboration were negatively associated with *JIF*, suggesting that an increased scope of domestic collaboration decreases the likelihood of publishing in better journals, perhaps due to

[44]The variance is much larger than the mean.

the transaction costs of collaboration. As expected, articles written in Chinese are more likely published in low-impact journals than papers written in English. Papers authored by researchers from elite Chinese research institutes or universities are more likely to be accepted in high-quality journals. Based on the values of the standardized coefficients of the variables, language is the factor most heavily impacting *JIF*. Indicated by the two interaction terms (*USCOLLAB* **PUB-AGE* and *USCOLLAB* **PUB-AGE*), the dynamic impact of international collaboration was shown to be statistically *in*significant.

Table 4.8:Regressions on the Journal Impact Factor

	Full Dataset (Panel 1)		CKM Longitudinal Data (Panel 2)			
	Model 1	Model 2	Model 3	Model 4 (Main Model)	Model 5	Model 6
	Negative Binomial	Negative Binomial	Fixed Effect	Fixed Effect	Negative Binomial	Negative Binomial
KMOD		0.21***				
*KMOD * PUB-AGE*		0.01				
AFTKMOD				0.94**		0.31**
*AFTKMOD * PUB-AGE*				-0.17**		-0.06**
USCOLLAB	0.55***	0.47***	1.07***	0.85***	0.44***	0.42***
*USCOLLAB * PUB-AGE*	-0.01	0.00	-0.24**	-0.18**	-0.08***	-0.07**
NUSCOLLAB	0.28***	0.28***	0.25	0.15	0.33**	0.25**
*NUSCOLLAB * PUB-AGE*	0.00	0.00	-0.07	-0.04	-0.05	-0.04
CHINESE	-2.41***	-2.40***	-1.80***	-1.79***	-3.40***	-3.41***
HONG KONG	0.48***	0.49***	0.30	0.39	0.00	0.04
CAS	0.31***	0.30***	-0.23	-0.16	0.12**	0.12**
ELITE-UNIV	0.27***	0.27***	0.49	0.46	0.07	0.08
AFFILIATIONS	-0.06***	-0.06***	0.35**	0.38**	0.09***	0.08**
PRC-CITY	-0.11***	-0.11***	-0.42**	-0.46**	-0.16***	-0.19***
AUTHORS	0.05***	0.05***	0.11**	0.11**	0.03***	0.03***
PUB-AGE	-0.04***	-0.04***	-0.05	0.08	-0.01	0.03

Note: *** p<0.01, ** p<0.05, * p<0.1

The above pattern remained after the variables *KMOD* and its interaction term with time *KMOD*PUB-AGE* were added to the regression equation (Model 2 in Panel 1). In addition, the results suggested that holding the variables of international collaboration, language, collaboration scope, publication age, authors' research capacity, and research discipline constant, papers associated with CKMs are more likely to be published in higher quality journals. This supported the role of knowledge moderators in upgrading China's research quality, providing further support for the above-mentioned "person argument"that authors who are involved in international collaboration are better scientists than those who do not. The effect of time (the regression coefficient of *KMOD*PUB-AGE*) was not statistically significant.

Longitudinal Publication Data of CKMAs

The Sacred Spark Hypothesis suggests that scientists differ with regard to their research performance (Allison & Stewart, 1974). Arguably, the research quality of an internationally co-authored paper is higher, not because of the occurrence of transnational collaboration but because the authors themselves are better researchers. Providing more convincing evidence of the impact of international collaboration on individual research performance, the estimates from longitudinal data are presented in the second panel of Table 4.8.

<u>Fixed Effect Regression vs. Random Effect Regression</u>

In the analysis of panel data, one must first decide whether to adopt a fixed effect or random effect model. This decision depends on whether or not the individual effects correlate with the explanatory variables (Wooldridge, 2002, 2006). Obviously, given the selection criteria of CKMs, the panel publications are not a random sample from a given population; so for the purposes of generalizability, a fixed effect model is preferred. In practice, the determination which model to use requires the implementation of the Hausman-Wu specification test (Greene, 2000). The STATA outputs are presented in APPENDIX D.1. The results suggested the existence of an individual effect; thus the fixed effects model was preferred.[45] These findings were also in line with the heterogeneous nature of CKMs discussed in the previous chapter.

The fixed-effect model equation is

$Y_{it}=\beta_0+\beta_t+\beta_1 Xe_{it}+\beta_2 Xc_{it}+a_i+u_{it,}$, where

Y is the dependent variable (i.e., research quality),

β_t is the time effect,

Xe refers to the list of explanatory variables,

Xc includes the list of control variables,

a_i is the individual fixed effect or unobserved heterogeneity of each CKM, and

u_{it} is the idiosyncratic error.

The first column of Panel 2 in Table 4.8 provides the fixed-effect estimates obtained by the within-groups method. The following discussion focuses on the fixed effects. The reference group consisted of CKMAs without authors from institution outside of China.

The coefficients of international collaboration variables (both *USCOLLAB* and *NUSCOLLAB*) denoted the expected difference between the impact factor of internationally co-authored articles and that of non-internationally co-authored articles with zero years of publication, that means 2006. These two statistically significant positive signs showed that for CKM papers published in 2006, the expected JIF of papers co-authored by US researchers was

[45] As APPENDIX D.1 shows, the Hausman test produces Prob>chi2 = 0.0033, providing strong evidence of a significant correlation between the unobserved person-specific random effects and the regressors. Thus, the null hypothesis is rejected because the difference in coefficients is not systematic, and a fixed effect model should be adopted (Yaffee, 2003).

about 1.07 higher than CKM papers without authors from the US, while the JIF of non-US internationally co-authored papers accepted by journals was on average of 0.25 higher than that of the reference group. So both H1 and H2 were supported in the longitudinal data.

The coefficient of the *PUB-AGE* (-0.05) indicated that, on average, the impact factor of CKM domestic papers was 0.05 higher than it was in the previous year. Notice that the coding mechanism of publication age indicated that later articles were associated with smaller values. The negative sign indicated that CKM papers without international co-authors also climbed up the ladder of journal visibility over time, although such annual increase was not statistically significant.

The coefficient of the interaction term *USCOLLAB * PUB-AGE (-0.24)*, that means, the discrepancy between the differences, suggested that with each additional year, the JIF for US-China collaborated articles was expected to be 0.24 higher than for Chinese domestic articles, indicating that the effect of US-China collaboration on the acceptance of Chinese-related papers (the JIF) increases over time. This finding did *not* support Hypothesis 4, which predicted that the impact decreases over the years due to knowledge accumulation resulting from "collaborative learning."

This widening gap of journal quality between international and domestic papers by CKMs could be explained by two reasons. One plausible explanation relates to better ideas or novel research methods, which facilitate successful international collaboration. Given the relative development levels of both the US and China in nanotechnology, taking the two-sided nature of research collaboration beyond quid pro quo (Hara et al., 2003) into consideration, it is highly possible that only those really interesting or promising research topics of CKMs can attract US collaborators. On the other hand, it may also suggest that "learning by doing" practices are not as influential as we expect reflected by journals to accept a paper for publication. In other words, what CKMs learned by collaborating on publications with US colleagues has not been transmitted to the CKMs' later work that is solely co-authored with *domestic* Chinese scholars.

On a more conservative note, the expected knowledge spillover funneled by CKMs may not have been recognized by the "gate keepers," possibly due to language barriers, a short observation period, selection bias, or other reasons.

This second explanation seems supported in Model 4 when *AFTKMOD* (the variable that denoted whether the paper is produced after or in the same of year the author became a CKM) and its interaction term with the publication year were added into the regression model. It is reasonable to believe that the knowledge moderation effect does not become apparent until the CKM has collaborated internationally twice, that means when the dummy variable AFTKMOD=1. Evidenced by a negative sign of the regression coefficient of *AFTKMOD * PUB-AGE* (-0.17), the CKM's knowledge moderation effect increases over time: holding other variables in the Model 4 constant, the mean impact factor of journals where the third and further internationally collaborated CKMA were published is expected to be higher than that of previous counterparts (i.e., CKMA which were published prior to the CKM's second international collaboration).

Also, interestingly, in both Model 3 and Model 4, the role of research capacity from the Chinese perspective disappears, contradicting the results of the full dataset (Panel 1). Individually and jointly, the regression coefficients of *HONG KONG*, *CAS*, and *ELITE-UNIV* were statistically *in*significant.[46]

For the testing of robustness, two more regressions on negative binomial regressions were carried out based on the nature and distribution of a dependent variable. As shown in Models 5 and 6 of Table 4.8, the results were relatively consistent. Comparing the estimation results in Model 5 & 6 (the panel dataset) with Model 1 & 2 (the full dataset), all of which use

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[46] The Wald test could not reject the null hypothesis that they were jointly 0 (Prob > chi2 = 0.18). The STATA output is listed in APPENDIX D.2.

the negative binomial regression estimate, it should also be noted that the coefficients of *USCOLLAB* in the longitudinal data were smaller than those in the full dataset: this provided more evidence to support the self-selection effect of international collaboration.

Table 4.9: Regressions on Citations

	Full Dataset (Panel 1)		CKM Longitudinal Data (Panel 2)			
	Model 1	Model 2	Model 3	Model 4 (Main Model)	Model 5	Model 6
	Tobit	Tobit	Fixed Effect	Fixed Effect	Tobit	Tobit
JIF	0.24***	0.23***	0.13***	0.14***	0.13***	0.13***
KMOD		0.10*				
*KMOD * PUB-AGE*		0.08***				
AFTKMOD				-1.26***		-1.15***
*AFTKMOD * PUB-AGE*				0.25***		0.24***
USCOLLAB	0.14***	0.08	-0.21**	0.05	-0.23**	-0.00
*USCOLLAB * PUB-AGE*	0.04***	0.04***	0.22***	0.14***	0.22***	0.14***
NUSCOLLAB	0.10***	0.10***	-0.02	0.13	-0.03	0.11
*NUSCOLLAB * PUB-AGE*	0.02***	0.02***	0.06	0.02	0.06	0.02
CHINESE	-0.30***	-0.29***	-0.39***	-.40***	-0.39***	-0.39***
HONG KONG	0.40***	0.41***	0.30**	0.29**	0.30**	0.22*
CAS	0.10***	0.09***	0.05	-0.01	0.04	-0.02
ELITE-UNIV	0.20***	0.19***	0.15**	0.18**	0.15**	0.12*
AFFILIATIONS	-0.04***	-0.04***	-0.08**	-0.11**	-0.08**	-0.10**
PRC-CITY	-0.11***	-0.12***	-0.03	.04	-0.02	0.03
AUTHORS	0.03***	0.02***	-0.01	-.02	-0.01	-0.01
PUB-AGE	0.25***	0.25***	0.22***	.05*	0.22***	0.06**

Note: *** p<0.01, ** p<0.05, * p<0.1

Paper Citations

Full Dataset

Similar examinations were also conducted for CITATION indicators, and Table 4.9 lists the regression results on log (*CITATIONS*).[47] Panel 1 (full dataset) produced results rather consistent with those shown in Table 4.8. Holding other variables constant, articles written in English are likely to be cited more than papers written in non-English. Articles authored by researchers from elite Chinese research institutes or universities are more likely to be cited by their colleagues. Knowledge-moderated paper are cited more than those that do not involve a CKM, and US-China collaborated papers on average obtain higher citation rates than domestic Chinese nano research.

Longitudinal dataset

Similar to the estimations on the JIF, both fixed effect regression and Tobit regression were applied to the longitudinal data. Below I also focused on the fixed effect (Model 3) to elaborate on the main findings here. Undoubtedly, holding other variables constant, on average CKMAs published in journals with a larger *JIF* are cited more frequently. The premium of the English language still holds and is even more apparent for CKMAs. Compared with the full dataset, the influences of collaboration scope and research capabilities from the Chinese side become either ambivalent or smaller in panel data. All of these findings were consistent with those in Table 4.8.

[47] Considering that e log (0) is meaningless, the dependent variable is calculated by log (citations+1).

The citation regressions told a slightly different story about the effects of international collaboration. The regression coefficient of *USCOLLAB* (-0.21) (Panel 2, Model 3) indicated that for articles published in 2006, the latest year of this examination, papers associated with US scholars received an average of 0.21 citations *fewer* than Chinese domestic papers without the US co-authors. This differed from the previous year, 2005. For CKMAs published in 2005 (when *PUB-AGE* takes the value of 1), the average number of citations for China-US co-authored papers was still 0.01 greater than that of Chinese domestic papers.[48] When we focused on the interaction effect (*USCOLLAB* * *PUB-AGE*), its coefficient suggests that, with each additional year, the expected increase in citations was 0.22 lower for China-US collaborative articles than for Chinese domestic articles. In other words, the citation premium of Sino-US CKM papers diminished until the year of 2006, when CKM domestic research started to attract more citations. This finding supported Hypothesis 4, which pertained to collaborative learning based on knowledge accumulation. The same pattern remained for the knowledge moderation variables (Model 4, Table 4.9): with each additional year, the expected citation increase was 0.25 lower for later CKMAs than earlier CKMAs. Model 5 and Model 6 present the results for robustness testing using a negative binomial model, which were consistent with those of the fixed-effect model.

Panel Attrition and Sample Selection

Since CKMs do not publish one nano paper per year, the panel was unbalanced with varied observable time periods of individual CKMs. The total number of observations was ΣT_i with T ranging from 1990 to 2006 and i ranging from 1 to 77. Given the nature of the data, one methodological concern about the unbiased estimate was panel attrition. Simply put, panel

[48] It is calculated by (-.21+.22*1+.22*1)-(0+0+0.22*1) =0.01

attrition occurs when an unbalanced panel results from a selection process related to u_{it}, or an idiosyncratic error. In reality, panel attrition is quite common when the studied entity (such as a firm or an individual) leaves the panel or fails to respond due to bankruptcy, mergers, death, or other explanations. Any type of panel attrition reduces the sample size, leading to a reduction in efficiency and precision of tests (Wooldridge, 2002; Wooldridge, 2006). If attrition is random or if it does not depend on the behavior we wish to study, estimates will remain unbiased. Otherwise, the presence or absence of an observation is not mean independent of the error, and a problem with endogeneity arises (Wooldridge, 2006; Greene, 2002).

The quest to untangle the sample selection problem in unbalanced panel data was initiated by Heckman (1976; 1979), who proposed three tangible solutions to deal with panel attrition. The first, a laissez-faire approach, simply ignores the problem, which works only if the missing data are random. The second way is to use weighted least squares (WLS) regression to file out the missing data based on observed values with a strong assumption of the time invariant feature of individuals. However, neither is applicable in the case of the CKM panel. Thus, the third approach, a two-step Heckman sample selection estimation method, was adopted to deal with this problem (Heckman, 1976, 1979; Wooldridge, 2006; Greene, 2000).

For the regression equation

$$Y_{it}=\beta_0+\beta_t+\beta_1 Xe_{it}+\beta_2 Xc_{it}+a_i+u_{it} ,$$

the selection equation can be denoted as

$$Y^*=Zg + e_{it} > 0.$$

Y_{it} is observed only if $Y^*>0$, where

$$\begin{cases} u_{it} \sim N(0, \text{sigma}) \\ e_{it} \sim N(0, 1) \\ \text{corr}(u_{it}, e_{it}) = \text{rho} \end{cases}$$

Given the selection rule of the CKM panel data, the outcome variable Y_{it}—research quality—was observed only when Y* was met. In this research, since CKMs were selected from Chinese nanotechnology publication databases, the latent variable Y* (i.e., the likelihood of the appearance of a paper in the CKM panel dataset) was determined by the following factors:

Language: Given the well-known coverage bias of the WoS database, CKMAs written in Chinese are less likely indexed in the WoS, and are thus less likely to appear in the database.

Table 4.10: Heckman Selection Model - Two-step Estimates: Longitudinal Data

	JIF		CITATIONS	
	Whole Model	Selection Model	Whole Model	Selection Model
VARIABLES	*JIF*	*USCOLLAB*	*CITATIONS*	*USCOLLAB*
JIF			1.01***	
*USCOLLAB * PUB-AGE*	-0.30***		3.62***	
CHINESE	-2.56***	-0.86***	-7.45**	-0.86***
HONG KONG	0.48		-1.78	
CAS	0.56*		-2.12*	
ELITE-UNIV	0.46		-1.63	
AFFILIATIONS	0.54***		-0.84	
PRC-CITY	-1.71***		0.14	
AUTHORS	0.16**		0.12	
RES-EXP		-0.02		-0.02
RESQ		0.00***		0.00***
USWRK		0.15*		0.15*
USVST		-0.25***		-0.25***
CNWRK		-1.60***		-1.60***
CNOTH		-0.09		-0.09
Lambda		-0.17		2.15*
Rho		-0.054		0.20
_CONS	3.295***	0.93***	-3.49	0.93***

Note: *** p<0.01, ** p<0.05, * p<0.1

Research experience: Extant studies have shown that research productivity of academic scientists follows distinct life cycles (Rauber & Ursprung, 2008; Levin & Stephan, 1991). Built on previous findings, a squared term of research experience was created to capture the quadratic (inverted U-shape) impact.

Proximity to the US: The selection criterion of CKMs dictated that they must be Chinese scholars who have collaborated with both Chinese and US institutions at least twice over a certain period. More and steadier connections with US affiliations increase the candidate's probability of producing joint publications with American scholars, and thus the probability increases that his/her publications will rotate into the sample.

Proximity to China: The same is true for their connections within China. In order to have their publications appear in the panel data, CKMs have to joint publish articles with peers in China. Closer relationships with Chinese public research institutes heightened the probability that their articles appear in the panel.

As suggested by Wooldridge (2006), the selection equation needed to be estimated first in order to compute the inverse Mills ratio. Then the outcome equation could be conditionally estimated according to observations with the inverse Mills ratio and Z as an instrument for Y*. STATA developed a program for realizing this function through the one step that was used here.

As illustrated in Table 4.10, the explanatory power of the selection model and the nonzero value of *rho* indicated that the Heckman selection model provides consistent, asymptotically efficient estimates for all parameters in the model. These results did not differ significantly from those of the fixed effect model; thus I could feel more confident about an analysis with a robust check. Moreover, the selection model, which supported Hypothesis 5, also revealed that, compared to visiting scholars, those who have established a formal relationship with a US affiliation are more likely to collaborate with American scholars and become a knowledge moderator.[49] This finding echoed a prior statement that social capital facilitates the new creation of intellectual capital (Nahapiet & Ghoshal, 1998). It also has policy implications for China's "exporting overseas, attracting back" policy, which is discussed in more detail in Chapter 6.

Summary

It is generally accepted that internationally collaborative papers appear in journals of higher quality and are cited more often than local research (Arunachalam et al., 1994). Yet it remains unclear whether this phenomenon is due to the self-selection of researchers, since only the best scientists collaborate at an international level (Barjak & Robinson, 2007; Bordons & Gomez, 2000), or the nature of international collaboration itself because of the syntheses of ideas and methods from different scientific communities (Burt, 2004). The deficiency of prior literature on this person vs. position argument has different policy implications. Analyzing the between- and within-group differences of research quality among CKMs in nanotechnology, this chapter tried to distinguish these two factors. The empirical tests provided evidence that supported both arguments for the influence of person and position in regard to the positive impact of international collaboration on research quality.

Secondly, this section identified other factors influencing research quality. Language, the missing variable in the estimation equation of former studies, turned out to be the most influential factor predicting the quality of Chinese nano research when measured by journal impact and paper citations. Thirdly, the findings also suggested that not all types of collaboration have a positive effect on research quality. This indicated that the argument about transaction cost largely holds. The diminished premium of Chinese elite research institutes on CKM research

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[49] This is indicated by the positive coefficient of variable *USWRK* (.15)

quality is particularly interesting, for it implied that encouraging non-elite universities to employ CKMs or to collaborate with CKMs is an effective way to alter the existing imbalances of research capacity in China, a deep-rooted problem in China's science system.

Last but not least, the discrepancy of regression results on *JIF* and *CITATIONS* told a different story about the dynamic impact of China-US collaboration on the quality of CKM research. The outcome of studying the two indicators of research quality was intriguing for two aspects. Firstly, from the evaluative bibliometric analysis perspective, each indicator reflected a particular dimension of the general concept of research quality. Such opposing results found in prior-publication peer review (journal editor's judgment) and post-publication peer review (researchers' citations) may suggest a difference between the views of gatekeepers and those of the scientific community on China's nano research quality. It highlighted the questionable validity of using a single measurement alone in research evaluation and echoed the appeal for "combining the various types of indicators in order to offer policy makers and evaluators valid and useful assessment tools" (van Leeuwen et al., 2003). Secondly, this finding suggested that a further examination of the sources of CKM citations is necessary, namely who cites CKM papers. If we believe JIF is a good indicator, the increase in citations may be explained by the fact that Chinese researchers are parochial and they frequently cite Chinese domestic paper for a variety of reasons, such as lack of access to better papers or a tendency to cite the work of domestic big shots, to name just a few. This effect was negligible in the past, but the growing numbers of Chinese scientists bring this effect to the forefront now (Leimu & Koricheva, 2005).

CHAPTER 5

INTERNATIONAL COLLABORATION AND RESEARCH TRAJECTORY

Introduction

As discussed earlier, this study adopted three indicators to gauge the impact of international collaboration and knowledge moderation on the development of nanotechnology in China. Chapter 3 showed the dominant role of the US in China's internationally collaborated research. Chapter 4 presented new evidence that quantified the role of the US-China collaboration and knowledge moderation in the research performance of CKMs as measured by two citation-based indicators. Until now, impact analyses have primarily focused on research quantity and quality. This chapter further explores this impact from the perspective of the research frontier. Largely explorative, a new method that tracks the shift of research content on the level of the individual scientist was developed based on turnover of keywords. This approach was first tested by three cases: two CKM cases and one benchmark case to assess the impact of international collaboration on the research direction of CKMs. A Probit model regression was also conducted to test the likelihood of CKM's changing research topics associated with the collaboration behavior.

Hypotheses

An unspoken norm in academia is that scientists actively push the research frontier within their capacity. Borrowing the notion of "creative destruction" from entrepreneurship literature, scientists seek to push their knowledge boundaries forward, rendering existing knowledge obsolete. Assume a knowledge moderator has a fixed knowledge stock K_i at the time t_i, denoted as $K_i \in [K_L, K_H]_{ti}$. Then his/her increased knowledge stock at t_j can be denoted as ΔK, in which

$$\forall\, j>i: \Delta K = K_j - K_i = [K_L, K_H]_{tj} - [K_L, K_H]_{ti} > 0$$

If t_j-t_i is close enough to 0, ΔK is expected to be marginally greater than zero, considering the bounded rationality of human beings. Applying this in the context of research stream, a change in the research topics of an individual scientist would be incremental rather than radical within a short period.

It is highly unlikely that one researcher could reorient his main focus of research overnight; thus, I hypothesize that a radical discontinuous change, if any, is triggered by an external impetus such as knowledge spillover associated with interactive learning (co-authorship). Built on the extant research and the development trajectory of both the United States and China, I posited the following hypothesis for testing:

H6: *The emergence of a new research stream of a Chinese knowledge moderator is related to beginning collaboration with US scholars.*

H7: *The new research stream triggered by US-China collaboration is further diffused within China.*

If H6 were supported, it would provide evidence supporting a leader-follower pattern within US-China collaboration and the impact of US-China collaboration on CKM's research streams. Hypothesis 7 attempted to untangle the question of whether or not the new stream triggered by US-China collaboration was picked up by the CKM and diffused to other Chinese domestic researchers. If H7 were supported, it would indicate an extended knowledge spillover from the US to China via the knowledge conduit of CKMs. In combination, the positive results of both hypotheses would suggest that CKMs are playing an important role in closing the knowledge gap between the US and China in nanotechnology.

Method

Measurement

Keyword was used as a proxy indicator of research topic. Stimulated by the idea of using "bibliometric fingerprints" for name disambiguation (Tang & Walsh, 2010), cluster analysis was developed to discern the emergence of the research stream of an individual scientist over time, if any, based on the dissimilarity of keywords in academic papers. This approach had two main goals: 1) to examine if the emergence of a new research line was related to the event of international collaboration; and 2) to explore whether the new stream triggered by international collaboration diffused further to other domestic Chinese scholars.

The unit of analysis was similarity in the focus of research of a pair of articles, measured by the research cohesion score (RCS), whose value was determined by the summation of shared keywords. Mathematically, the research cohesion score can be denoted as

$$\mathrm{RCS}[i,j] = \sum_{i=n}^{i=1} \sum_{j=n}^{j=1} [\mathrm{A} * \mathrm{K}]_{n*m}$$

where

A is the collection of the publications of an individual scientist, $\mathbf{A} = \{a_1, a_2, \ldots, a_n\}$

K is the set of selected keywords reported by **A**, and $\mathbf{K} = \{k_1, k_2, \ldots, k_m\}$.

Different from the algorithm proposed for the identification of authorship, no weighting was used here. However, to reduce the confounding clustering impact introduced by sharing common keywords, this study manually excluded terms such as "preparation," "particle," "synthesis," "investigation," "effect," and "characterization" from the selected field of keyword.

It should also be noted that using keywords to track the evolution of a research stream, one hurdle must be overcome: identifying *real standardized* nanotechnology keywords. This challenge was addressed, or at least reduced, by the following three sequential steps of cleaning: 1) automatic cleaning using VantagePoint, a text mining software, by which fuzzy matching and thesauri were used to remove uninteresting stopwords (very common words); 2) several rounds of manual keyword standardization and cleaning to consolidate certain nano term variations using regular expressions; and 3) validation from researchers in nanotechnology on keyword "synonymies," that is, different keywords and their variants denoting the same concept or topic in order to reduce the issue of substitution.

The process of analysis proceeded as follows. The set of publications associated with a targeted researcher was first extracted from the CKM dataset. The corpus of keywords was then obtained from a composite keywords field that included three sets of keywords offered by the author and structured by the journal, and title phases achieved by the natural language processing (*NLP*) function in text mining software.[50] The generation of this field of composite keywords can be justified in two ways. Firstly, not every article contains either keywords reported by the author or keywords structured by the journal. In Chinese nanotechnology publications, the coverage of keywords (author's) and keywords Plus are 65% and 90%, respectively. Secondly, my past research experiences working on Chinese nano publication data suggest that the combination of the above two keyword fields with a title can best capture the research content of articles.

Once the standardization and selection of keywords were complete, a 2-D matrix of the article * selected keywords was created. The clustering function in the R program, which produces different groups, was used. So that the linkages of different articles written by individual authors could be visualized, the concept of an approximate structural equivalent (ASE) in social network analysis was also applied. Simply put, in a single-relation network, actors within a structurally equivalent cluster are more similar than those outside of the cluster (Wasserman & Faust, 1994; Hanneman, 2004). Upon application of this notion to the identification of research continuity, two articles were considered approximately structurally equivalent if they were similar in the position of written keyword(s) in an article-keywords

[50] They are keywords (author's) and keywords plus, shown in WoS data, and phrases extracted from the title.

bipartite network (Pieters, Baumgartner, Vermunt, & Bijmolt, 1999). Articles allocated to different clusters indicate different research lines. Figure 5.1 illustrates the process. For more details of this method, readers can refer to Tang & Walsh (2010).

Considering the incremental research shift within each researcher's career over time, transitivity is imposed using a hierarchical clustering with a single linkage. Thus, if the research cohesion score determined that AR_1 and AR_2 fit into the same research line and that AR_2 and AR_3 discussed the same research subject, then AR_1, AR_2, and AR_3 were aligned with the same research cluster even if the two research papers (AR_1 and AR_3) themselves had no shared keywords. This process was iterated via R program until all transitivity matches were completed.

Analysis

To explore the linkage of CKM's research stream dynamics and international collaboration, I started with three cases: two CKMs and one benchmarking researcher to compare their continuity of research subjects reflected by keywords turnover in their nano articles.

Two CKM Cases

Two Chinese nanoscientists out of 59 CKMs who are currently working in China were intentionally chosen to advance our understanding of the relationship of keyword turnover and international collaboration. The selection criteria were based on a balanced consideration of the follower factors: 1) region—eastern China vs. western China; 2) university rank—elite university vs. non-elite university; 3) research sub-domain—nano material vs. nanobiology; and 4) age cohort—middle career researcher vs. senior researcher.

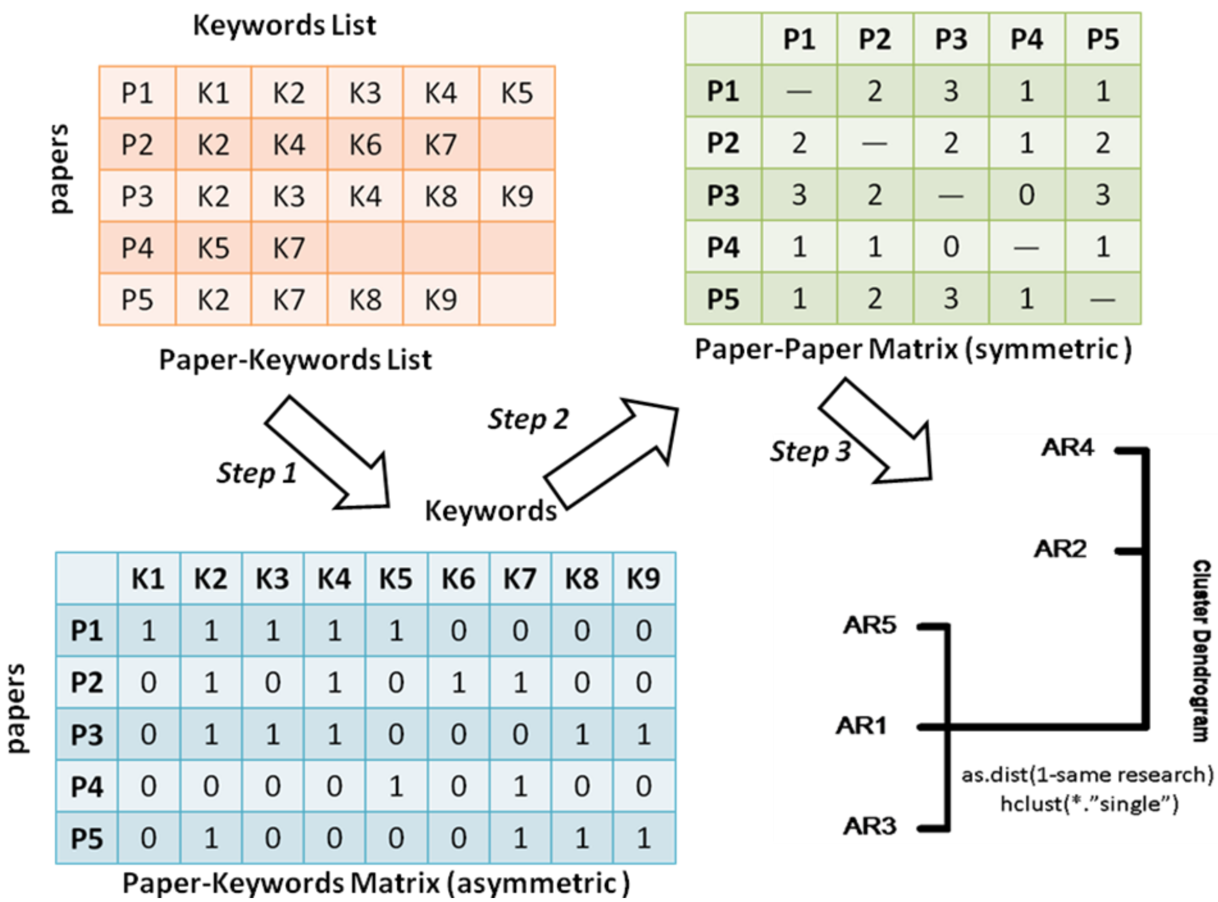

Figure 5.1. Illustration of identifying new research streams by keywords analysis

Note: Adapted from *Visualizing the intellectual structure with paper-reference matrices*, by J. Zhang, C. M. Chen, and J. X. Li, Nov.–Dec. 2009, Paper presented at the conference IEEE Transactions on Visualization and Computer Graphics.

Case 1: Nano materials—Zu, Xiao Tao

The first selected case was Xiao-Tao Zu (祖小涛), a mid-career researcher at a middle-ranked university in western China. Born in 1965, Zu gained his doctoral degree from Sichuan University (China) in 2002. Funded by the Chinese government, Zu visited the Department of Nuclear Engineering and Radiological Sciences at the University of Michigan as a visiting scholar from 2001 to 2006. Zu is a full professor in the School of Physical Electronics at the

University of Electronic Sciences and Technology China (UESTC) in Chengdu. His main research focuses on optical irradiation, nano composites, and intelligence structure. According to the Chinese nanotechnology publication database, Zu has co-authored 16 papers in nanotechnology in the time period from 2001 to 2006. Among them, ten (over two-thirds) were the result of a collaborative effort with scholars at the University of Michigan where he was located before.

Following the process of keyword cleaning, a matrix of 16 articles *116 keywords was generated. The clustering threshold was set at 2; that is, articles sharing two or more keywords were assumed to have the same research topic. As shown in Figure 5.1, seven structurally equivalent clusters emerged from the corpus of publications by Zu, Xiao Tao, suggesting seven different research subjects that Zu pursued during that period. For the purpose of illustration, the dendrogram in the figure provides information for the paper code,[51] the publication year, and collaborating countries. As depicted in the figure, except for one large cluster, the other six clusters were all singletons, in which four clusters (AR1, AR2, AR3, and AR11) were Chinese domestic papers and two (AR16 and AR4) were the outcomes of US-China collaboration.

A closer examination showed that these six articles pertained to different research topics. AR1 discussed a laser-induced damage mechanism, AR2 investigated hydrogen embrittlement of a Ti-Al-Zr alloy, AR3 focused on the process of the preparation of the TiO2 nano crystal, while AR11 explored the properties of the photoconductive UV detector. None of them shared more than two keywords and were thus clustered separately (APPENDIX E.1). In the same vein, AR4 and AR16, both of which involved scholars from the United States, examined irradiation-induced martensitic transformation and the structure of Ti-Al-Zr alloy in high-temperature alkaline steam,

[51] The 16 articles were first sorted alphabetically according to title and then labeled from AR1~AR16. The responding titles of the codes are shown in Appendix E.1.

respectively. Each of them that also stood out as a unique research stream was assigned a unique group given the low degree or lack of shared keywords.

Zu, however, did commit to specific research as reflected by the largest cluster, containing ten nano articles. A close inspection of the abstracts of these papers indicated that they all investigated the optical or magnetic properties of specific nano particles or nano composites. Among these ten papers in this cluster, the earliest one examining the structural and magnetic characterization of CoxNi1-x nano particles, was co-authored by Chinese scientists at Dalian University of Technology, the University of Electronic Science & Technology, and US scholars at the University of Michigan in 2003. Later, another nine research papers, which pertained to the same topic, included 12 additional co-authors and two additional Chinese institutions, the Chinese Academy of Science and Sichuan University (Appendix E.2). In other words, by collaborating with his peers in the US, Dr. Zu continues his research that was initiated as a US-China collaboration. This provided some evidence in support of both hypotheses 6 and 7 on the impact of US-China collaboration on the advancement of China's research frontier.

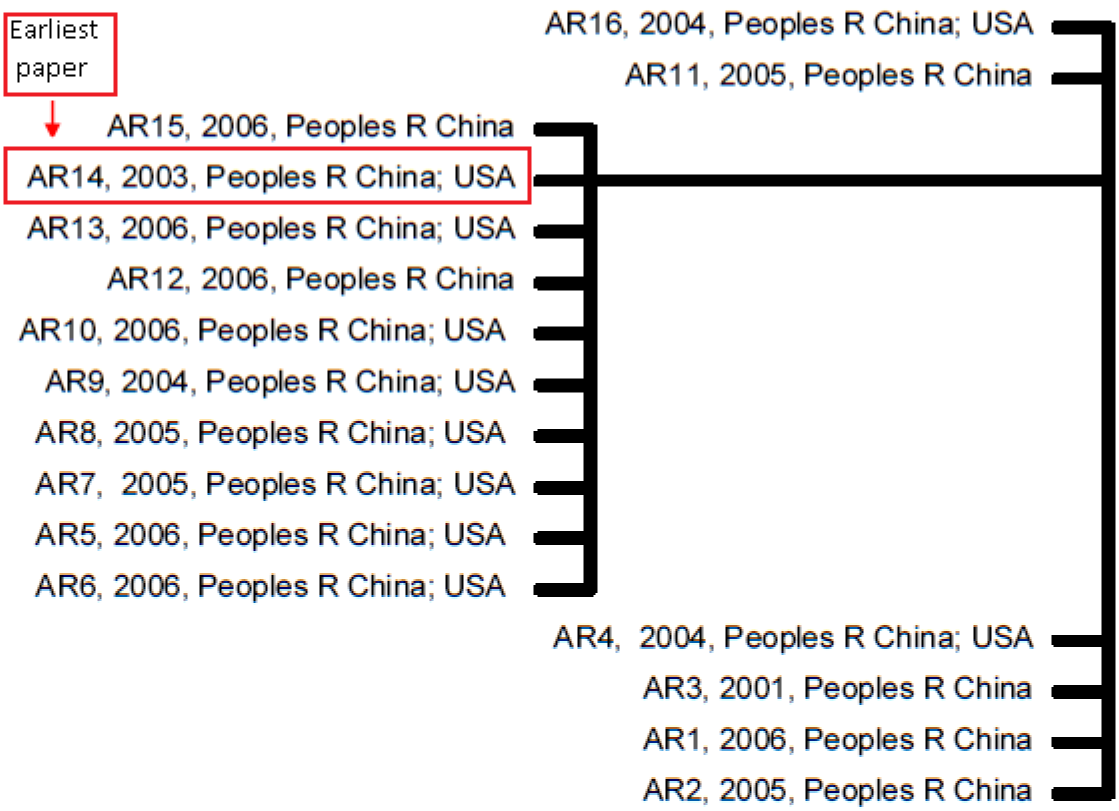

Figure 5.2 Cluster dendrogram of the research streams of Zu, Xiao Tao

Case 2: Nanobiotechnology: Chen, De Pu

The second selected case was De Pu Chen (陈德朴), a senior researcher in a Chinese elite university. Graduated from Tsinghua University in 1970 in chemical engineering (bachelor's degree), Dr. Chen obtained his doctoral degree in chemistry from the Chinese Academy of Sciences (CAS). From 1997 to 1999, he visited Miami University as a government-funded senior visiting scholar, and since that time, he has been a professor at Tsinghua University. His research focuses on probing the photoluminescence properties of semiconductor nano crystals, their applications in biological fluorescent probes, and DNA purification and gene typing. According to his online curriculum vita, Dr. Chen De Pu has published more than 60 articles and filed ten patents.

Dr. Chen has authored 19 nano papers found in the Chinese nanotechnology dataset. Two articles resulted from collaboration with colleagues in the US, and one involved researchers in Japan. Repeating the same analytical procedures, the matrix of 19 article * 114 keywords was created. Running the same script, the R program produced four clusters based on the research distance reflected by keywords.

Figure 5.3 illustrates the four research streams that Dr. Chen has pursued in the domain of nanotechnology. One singleton cluster, AR10, described the sol-gel process of generating alpha-Fe2O3 nano particles. AR6 and AR19 related to research in x-ray lithography. The third research stream, which is also apparently Dr. Chen's focus, explored the structure, properties and application of nano crystals and various nano particles. In addition to research initiated in past projects, a keyword analysis also identified a new research line in which Dr. Chen was engaged in 2004. As shown in Figure 5.3, the fourth cluster consisted of two papers (AR3 and AR8), both of which were the outcome of US-China collaboration. Reading the abstracts showed that these two articles investigated approaches to using magnetic nano beads to extract genomic DNA.[52] Again, we saw some evidence of the impact of US-China collaboration on the increasing knowledge stock of Chinese knowledge moderators (H6). However, possibly due to the truncated data in both discipline and time, we could not find evidence for extended knowledge spillover (H7).

[52]The correspondence of article coding in the dendrogram and the title of the research paper are listed in Appendix E.3.

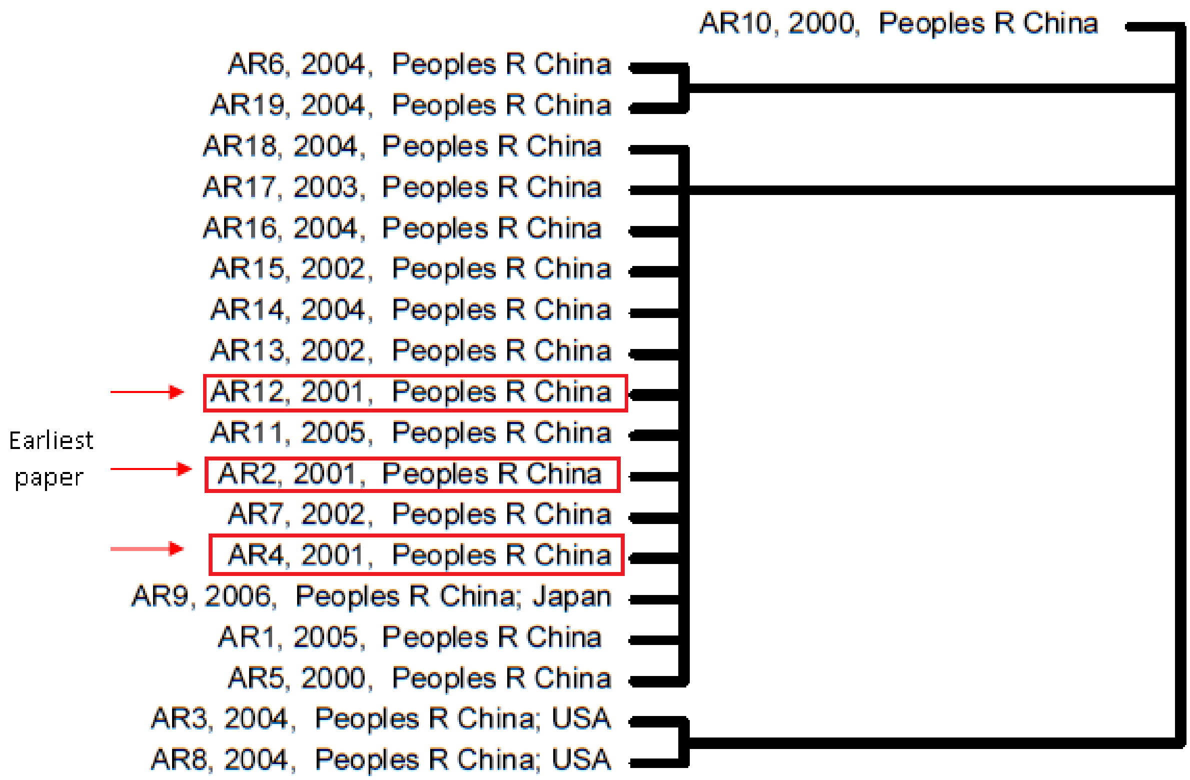

Figure 5.3: Cluster dendrogram of the research streams of Chen, De Pu

Benchmarking Case

<u>Case 3: Nano electronics, Jiang, Ya Dong</u>

To some extent, the above two CKM cases provided evidence in support of the influence of US-China collaboration on the choice of research topics of CKMs. However, it remained uncertain whether this would also hold true for non-CKMs. For robustness testing, a third researcher who has not published internationally collaborative articles in nanotechnology was also tested with this method.

Ideally, the benchmarking case should be similar on all dimensions except the independent variable—collaborating with the US—and the dependent variable—change of research subject (Przeworski & Teune, 1970). In reality, however, such restrict matching criteria are hardly met. Thus, the following matching criteria were proposed for the benchmarking case selection:

1) The nano researcher did not collaborate with scholars outside of China in the period of 1990–2006 (at least as reflected in the Chinese nano dataset).

2) The researcher is affiliated with an institute of the same or similar research ranking as either case 1 or case 2.

3) The researcher has an equivalent number of publications as either Case 1 or Case 2.

4) The researcher has similar research experience as either Case 1 or Case 2.

One case, Dr. Ya Dong Jiang (蒋亚东), who satisfied the above four conditions, was identified. His online curriculum vitae suggested that his research experiences are somewhat comparable to those of Xiao Tao Zu (Case 1). Born in 1964, Jiang received his doctoral degree from the University of Electronic Science and Technology of China (UESTC) in 2001, one year earlier than Xiao Tao Zu. Since then, he has worked there. Currently a full professor in UESTC, Jiang was named a "Yangtze River Scholar" by the Ministry of Education of China in the field of microelectronics and solid state electronics. Based on his online curriculum vitae, he has published 70 papers and applied for three patents.

The Chinese nanotechnology publication dataset identified 14 validated articles authored or co-authored by Ya Dong Jiang.[53] After the matrix of 14 articles * 52 keywords was generated, the same R script was executed and yielded only one cluster (Figure 5.4). This was especially interesting considering that fewer keywords lead to a lower likelihood of sharing, and thus larger

[53] The correspondence of article coding in the dendrogram and the title of the research paper are listed in Appendix E.4.

likelihood of multiple clusters. The result was in sharp contrast with that of Zu, Xiao Tao. A further examination of the research content that entailed reading their abstracts showed that Jiang's articles focused on the properties, fabrication, and applications of Langmuir-Blodgett films and self-assembled polyaniline.

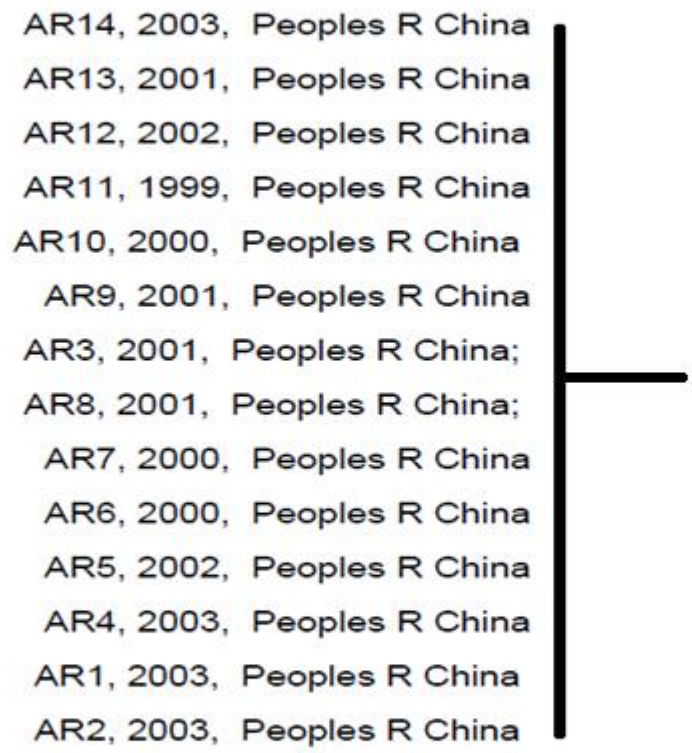

Figure 5.4 Cluster dendrogram of research stream: Jiang, Ya Dong

Analysis

As mentioned, the three illustrative examples were used to demonstrate the turnover of keywords associated with international collaboration. Based on the clustering results in the dendrograms, we were able to observe whether or not and when an individual scientist starts publishing on topics that depart from their past field of expertise. Two alternative explanations can be advanced explaining the radical changes in research subjects. One is that the departure from previous research indicates creative efforts resulting from autodidactic learning. On the other hand, the turning point of intellectual research is possibly due to knowledge spillover resulting from the joint publishing process, that is, collaborative learning (H6). In the latter case, there also two possible scenarios: firstly, it is also possible that the emergence of a research stream introduced by the co-authors of the CKMs is digested by the CKMs and diffused further domestically in the process of joint publishing with Chinese scholars. Of course, it is also likely that the “fake” emergence of the research stream was entirely introduced by foreign co-authors and never picked up by Chinese co-authors. Recall Dr. Chen’s research on extracting genomic DNA via nano beads (Case 2, AR3 and AR8). This topic, which appeared in Chen’s research in 2004, significantly departs from sub-fields in which Dr. Chen had already been active. However, since then it has not reappeared in his subsequent nano papers until the middle of 2006. Given time truncation, it remains uncertain whether Chen had made any new advancement in that topic area or if his stream had further diffused through collaboration with domestic Chinese scholars.

A researcher’s understanding on a specific research subject advances over time. Such research progress can be visualized via heat maps, which were originally used in molecular biology to compare genes across different samples. Heat maps were adopted here to graphically represent data where the values taken by a variable (here research cohesion scores) in a two-dimensional map. This method reorders articles along horizontal and vertical axes and color-codes cells based on research cohesion scores. The results demonstrated by Figure 5.5 can be interpreted in two ways. Based on the left side of the dendrogram and to the top of the heat maps, we find the same but abbreviated information as Cluster Dendrograms (Figures 5.2–5.4) show. And the other is based on the shades of color-coded cells (Barrow, Headley, Peru, & Derrick, 2009). As demonstrated in all three cases, articles on the same research topic do not share exactly identical keywords. As shown in the heat map, articles within a cluster do not have only one solid color. This not only reflects the necessity of imposing transitivity but also indicates researcher’s incremental knowledge accumulation within each research stream over time.

Case 1: Zu, Xiao Tao

Case 2: Chen, De Pu

Case 3: Jiang, Ya Dong (benchmark)

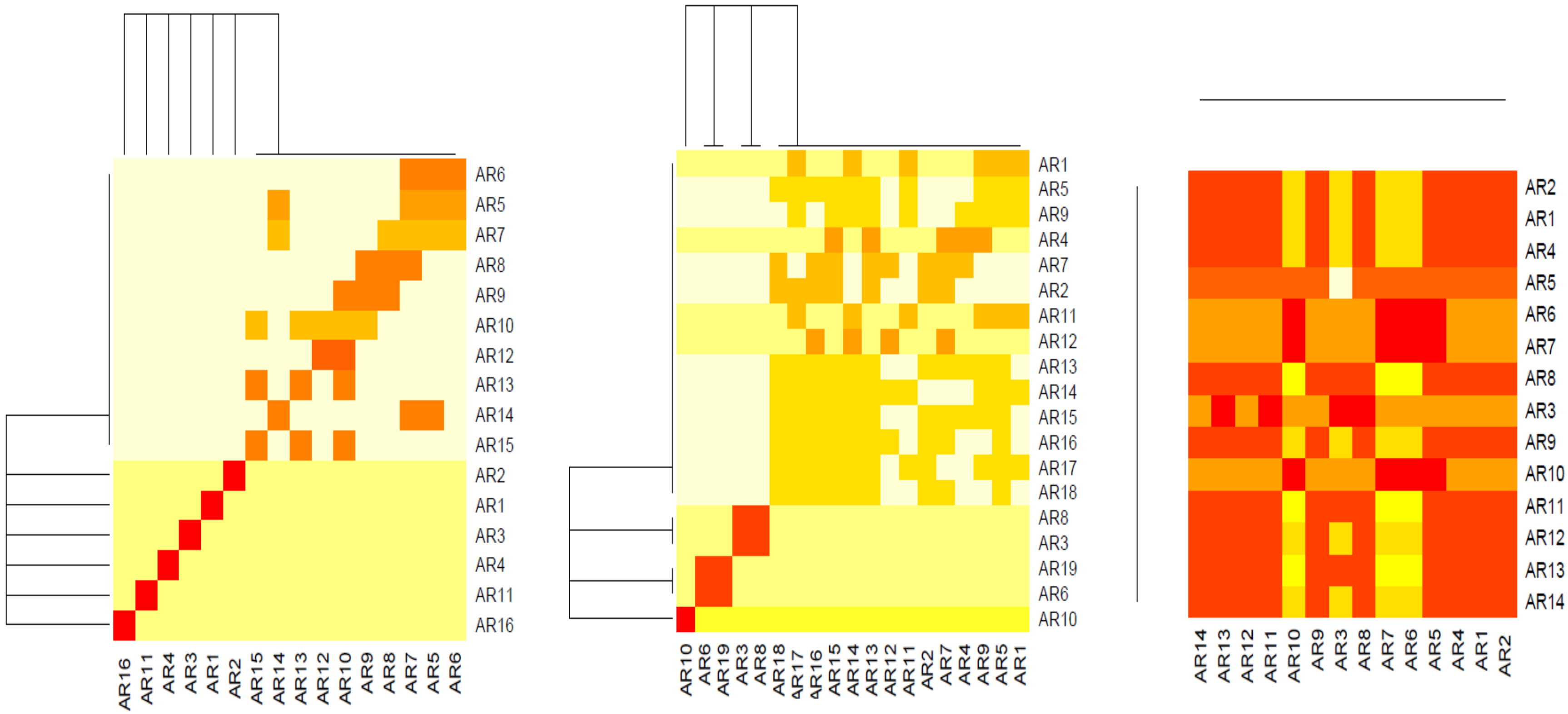

Figure 5.5 Heat map on the research stream of three cases

Statistic Testing

Following the illustrating case studies, I took a further step by statistically testing the linkage between Sino-US collaboration and radical changes in research topics for all 77 CKMs. Due to data availability, only H6 was tested.

The unit of analysis was each article per se. Similarly as in the above three cases, I ran a cluster analysis for each CKM separately based on the similarity of their research reflected by RCS. This assigned each article with a group ID. The dependent variable *DELTA* indicated whether the research subject of the article departed from CKM's previous research or not. If the paper was located in a group that is different from all his/her previous publications, *DELTA* was coded 1, otherwise 0. Since the coverage period ranged from 1990 to mid 2006, all publications of each CKM in his/her first year were excluded. This left 2119 articles in total for analysis.

The independent variable was US-China collaboration (*USCOLLAB),* and the control variables included scope of research collaboration and publication year. The Probit regression result is presented in Table 5.1. The Panel 1 tested H6 for all the CKM's research history in general, while Panel 2 differentiated this effect by three sub-fields of nanotechnology: nano materials, nanobiotechnology and nanomedicine, and nano electronics and devices. As shown, collaborating with the US colleagues in general increases CKMs' likelihood of shifting their research topic, and this effect was particularly apparent in the field of nanobiology. This finding was consistent with the comparable strengths of the US and China respectively in sub-fields of nanotechnology: the US possesses greater strength in nanobiology areas, whereas China's strength lies more in the materials science area (Tang & Shapira, 2011). All count R squares in Table 5.1 are rather high, suggesting at least 82% of cases were correctly predicted by these models (Long & Freese, 2006). APPENDIX E.5 reports the LSTAT output for the overall model (Model 1).

Table 5.1: Probit Regression on Shifting Research Topics

	CKM Data (Panel 1)	CKM by Sub-fields (Panel 2)		
	Model 1	Model 2 Nano mat	Model 3 Nanobio	Model 4 Nano elect
USCOLLAB	0.25*	0.15	1.05**	0.01
COUNTIRES	0.10	0.30*	-0.32	0.01
PRC-CITY	0.19***	0.28***	0.91***	0.01
AUTHORS	0.03*	0.05*	-0.01	0.01
PUB-AGE	0.10***	0.09***	0.43***	0.09***
Num Obs	2119	1152	266	701
Count- R2	82.68%	82.99 %	85.71 %	82.45 %

Note: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Summary

In sum, the combination of information gathered from empirical testing and three cases indicated the following findings. First, hypothesis 6 was supported by evidence: US-China collaboration was associated with an individual researcher's entrance into a new sub-field. Although all three researchers, including two CKMs and a benchmarking case, demonstrated incremental changes in their research streams, some radical changes are linked to the event of international collaboration. This also suggested that scientific collaboration among Chinese and US scientists has prompted further advancement on some topics that may otherwise not have taken place. Secondly, the two CKM cases showed that two possible scenarios may have taken place after CKMs became involved in new lines of research with US American colleagues: They could have picked up a new research stream and further explored it with domestic Chinese scholars (Case 1), or they confined such investigation without further extending knowledge spillover by co-publishing with domestic Chinese scholars (Case 2). So Hypothesis 7 was only *partially* supported here. Thirdly, Cases 1 and Case 2 showed that CKMs enable all Chinese scholars to exchange ideas and work practices with the western colleagues with whom they have worked. In other words, after visiting Chinese scholars have left their American host institutes, they continue to collaborate with the researchers of their former host institutes. It provided some evidence that CKMs make national boundaries more porous for knowledge dissemination between the US and China. This finding supported the enduring proposition regarding social capital that people may leave but are not forgotten (Agrawal & McHale, 2003).

CHAPTER 6

DISCUSSION

Findings

China’s status as a scientific power, particularly in the emerging area of nanotechnology, has become widely accepted in the global scientific community. The explosive growth of China’s S&T is currently a topic of great interest from the perspective of both academia and public policy. This study posited that US-China collaboration and knowledge moderation play a critical role in China's inexorable growth in this promising field. The key research question for the study—does the US-China collaboration impact China’s rise in nanotechnology—was addressed by evidence from several sources.

First, this study found strong evidence to support China’s emergence as a leading nation in nanoscience and nanotechnology. Contrary to the common convention, evidence confirmed that China was an early success in this nascent field (Shapira & Wang, 2009). Reflected by US-China collaborative articles, the astonishing growth of nanotechnology in China goes beyond quantitative expansion, for both qualitative and structural changes are also occurring even though they have not changed significantly. In terms of research content, most sub-areas in which the US and China have collaborated are those in which China has traditionally been strong, while many of China’s best public research institutes (PRI) and universities have co-authored papers in these sub-areas with a diverse body of collaborators in the US.

This project has found new evidence to support the positive impact of US-China collaboration on the quality of Chinese scholars’ research, which was always in question due to the effect of self-selection. The higher research quality of internationally collaborated papers as measured by higher citation rates and JIFs suggested that collaborating with US scholars positively impacts CKM’s research quality. The fact of a shrinking difference in citation rates between US-China collaborated papers and domestic Chinese papers further underscored how collaborative learning closes the gap between the two countries. The diminished premium of Chinese elite research institutes in US-China collaboration was a particularly interesting finding, for it implied that encouraging non-elite universities is an effective way of reducing the inequitable allocation of education resources, a deep-rooted problem in China.

And additional finding of this research concerns research stream: US-China collaboration is associated with the development of new or unique research stream(s) for individual researchers. By collaborating with western scholars at institutions that they have visited before, CKMs themselves not only enter into the study of new sub-domains in nanotechnology but also instigate knowledge spillover across national borders by further collaboration with other domestic Chinese scholars.

Limitations

The study had some limitations. To begin with, this research assumed that nanotechnology development in China could be captured by the quantity, the quality, and the research content of nano publications archived in SCI-WoS. Thus, all publication data included in this research were drawn from indexed records in the Web of Science. However, as the most standardized publication dataset for scientific research analysis (Levin & Stephan, 1991; Stephan & Levin, 1991; Turner & Mairesse, 2003), WoS contains a certain degree of bias. For one, it demonstrates a clear bias in favor of US publications and strongly neglects non-English publications. In Duque's words, this is inadequate as "indicators of scientific productivity outside the developed world" (Duque et al., 2005). Indeed, most Chinese scholars, similarly to scholars in many other non-English countries, still publish in domestic Chinese journals, most of which are not collected by the SCI database.

This sample selection impacted the analytical results of this study. To be more specific, the coverage bias of WoS minimizes the impact of international collaboration on research quality because it is reasonable to believe that most Chinese articles invisible to WoS are of mediocre quality. Hence, if they were included, the positive impact of international collaboration and knowledge moderation would have been higher. In the same vein, in terms of the impact on China's research stream, the missing articles published in lower-quality Chinese journals may conceal extended international knowledge spillover triggered by the collaboration between CKMs and their domestic colleagues.

Secondly, not all Chinese scientists who intensively collaborated with the US colleagues were included in our sample. Given the notorious problem of name ambiguities, only 77 CKMs were included for three chosen sub-domains of nanotechnology. The selection of CKMs leaned toward successful international collaborators. Accordingly, the extent to which these identified scholars could represent CKMs who bridge the scientific communities of both the US and China through intensive collaboration remains unclear, which may have impacted the study findings in two directions. Without any out-of-sample information, we had no way to ascertain, let alone correct for, this potential source of sample selection bias.

The third potential source of bias was introduced by two-dimensional truncated data, that is, the time and disciplines of the publication dataset. Recall that the analyzed data in this study were nano articles published from 1990 to 2006 and indexed in ISI-WoS. Confining the investigation to nanotechnology papers and a limited 16-year time window posed a threat: this may lead to either exaggerating the direct spillover effect from Chinese international collaborators or hide the *indirect* spillover effects originating from them and their collaborators. For example, Chapter 5 found some evidence for the idea that international collaboration brings about radical rather than incremental change at the level of domestic collaboration. Certainly, these three cases cannot speak to the impact of US-China collaboration on CKMs' research frontier since new streams are likely to stem from CKMs' past research prior to 1990. These limitations suggest caution in generalizing the results and the policy implications of this study, both of which are discussed below.

Contributions

Notwithstanding the above-mentioned limitations, this research had intellectual merit in the following three aspects. Firstly, the study utilized a multi-method approach to exploring the dynamic pattern of US-China collaboration and its impact on China's nanotechnology research development. The combination of using bibliometric analysis, empirical testing, and case studies allowed for the development of a comprehensive assessment of international research collaboration in this emerging field. Secondly, this project developed a concept of CKMs and used it as a prism to reflect the impact of collaborating with US scholars on the nano research performance of Chinese scholars. The proposal of this notion allowed me to do the following: 1) to examine an extended international knowledge spillover within China; 2) to model factors influencing the growth of China's research quality; 3) to identify and characterize a special group of scientists who facilitate knowledge diffusion by forming intensive collaborative networks with Chinese and US scholars. Thirdly, past literature has not been able to adequately investigate the impact of knowledge spillover on nanotechnology development. One challenge facing the literature pertaining to this subject is the difficulty of empirically measuring spillovers. Departing from previous literature, which adopted only citation-based indicators to examine such an impact, this study also experimented with a new method of identifying the unique research stream(s) of an individual scientist and checking if any discontinuity in the research topic was correlated with a case of international collaboration. From a methodological standpoint, it was an important step in the research evaluation domain.

As an empirical research study, the contributions of this project mainly concentrated on methodological perspectives. However, theoretical implications also presented themselves. The project provided evidence to support both human capital and social capital theories reflected by person vs. position arguments. On the one hand, the cross-sectional regressions indicated that knowledge moderators demonstrate better performance than their counterparts. On the other hand, after controlling for the self-selection effect (fixed effect regression in panel data), the event of collaborating across national borders has a positive impact on research quality. The phenomenon of social capital facilitating the generation of knowledge creation supported Burt's idea of the structural hole, which posits that the syntheses of ideas and methods from different scientific communities generate better ideas and practices. This study also supported the enduring social capital proposition that people leave but may not be forgotten. This finding showed that the majority of Chinese knowledge moderators have visiting or study experience in the United States. For those who have left their American host institutes, they continue to collaborate with the researchers of their former host institutes.

Policy Implications

This dissertation research project also has broad policy implications. In spite of imbalanced strengths, both the US and China have important economic, political, and military interests that encourage cooperation and collaboration with each other. With expanding research exchange, the manner in which knowledge spillover occurs and its impact will have significant implications for the development of both countries.

From China's perspective, international scientific collaboration can also represent a "double-edged sword." Chapter 4 and Chapter 5 provided some evidence supporting the positive impact of international collaboration on China's research quality and research content. Recall that Chapter 3 demonstrated that China's nanotechnology research development is internally driven in terms of research quantity. This underscores the importance of domestic research activities. In fact, due to a variety of reasons the majority of Chinese scholars do not have the resources, opportunities, or capacity to collaborate with overseas scientists. Thus, the Chinese government should not only strengthen mechanisms that encourage collaboration with the US but also facilitate the expansion of knowledge diffusion by encouraging Chinese scholars who collaborate with US scientists to increase their collaboration with domestic colleagues in order to create a "snowball effect" and magnifying the benefits of existing collaboration efforts. It should be also noted that one great idea or one top-notch technology is of greater benefit than one hundred mediocre ideas. Whether a researcher collaborated or not is not the only factor of import, but the content and quality of the outcomes of this collaboration are seminal. It is critical for Chinese R&D managers that they go beyond assessing quantity of internationally co-authored papers and include general collaboration and the breaking of new frontiers in their assessments. Thus the suggestion for China's R&D policy makers is "to harness their newly acquired know-how" through international collaboration and amplify the knowledge spillover by further collaborating with domestic colleagues on various research fronts.

On the other hand, as revealed in Chapter 3, the scientific domains in China and the US have collaborated are most often fields in which China has been traditionally strong. A shifting research agenda triggered by collaborating with US peers may suggest that nanotechnology development in China will advance, but it may also indicate the passiveness of Chinese researchers when it comes to choosing research topics. This potential shift in research stream arguably undermines the utilization of R&D investment for China's own needs. This problem is particularly critical given the weak linkage between science and industry, a deep-rooted problem of the Chinese national innovation system. The knowledge created through international collaboration may not translate into innovative technology, but has been used to enhance the welfare of the economy and the society in the US. If distribution of resources goes to too much "R" but too little "D," this can lead to considerable wasteful R&D expenditures that force China to remain in the exploration stage of science rather than the exploitation stage of investment. From this viewpoint, it is debatable whether pursuing state-of-the-art research topics is fruitful or whether it "tilts research away from those relevant for national development" (Baty, 2009); in other words, whether innovative scientific pursuit beyond industrial capacity results in gains or losses for China remains arguable.

This project also shed some lights on human capital management and public R&D allocation in China. In spite of its pronounced growth in R&D investment, China's research policies are presenting several significant challenges, one of which is the deeply-rooted problem of huge regional disparities in the development of science and technology. For some time now, the Chinese national government has pursued a modeling strategy of allowing only a few regions to develop. This preferential policy favors coastal areas, which possess stronger physical and human capital resources than those in other parts of the country. The result is a "four-world" China. While the eastern seaboard region, the "first world," which is home to only 2.2% of the Chinese population, has reached a level of economic performance similar to some developed countries, the "fourth world" of China, where approximately half of the population lives, has an average per capita income below that of other developing countries. A similar profile can be found in the distribution of R&D resources. Whereas a majority of elite Chinese universities and CAS are located in coastal provinces and special development zones in southern and eastern China, only a few are located in inland areas. This unequal distribution of research institutions contributes to the disproportionate distribution of national research projects, which reinforces investment of resources in the wealthier coastal areas. This huge disparity has been a major challenge for sustainable development in China. Empirical evidence that showed a decreased premium of elite Chinese universities shed some light on the mechanism for promoting science and technology development in underdeveloped regions: selecting scholars from non-elite Chinese universities for international visits.

In addition to research collaboration per se, a more important policy impacting both China and the US is the mobility of researchers. The era of globalization has promoted mobility in nearly every domain: resources, commodities, capital, and more importantly, talent. For a long time, the literature pertaining to the mobility of talent focused on the phenomenon of the "brain drain" and its negative impact on the countries sending talent to other countries (Adams, 1968; Collins, 1988; Laudel, 2003; Massey et al., 1993). In the last decade, the increasing phenomenon of reverse migration and, accordingly, knowledge spillover has drawn intense attention in both advanced and less advanced economies. Florida (2005) claims that the US is losing its magnet for global talent, evidenced by a continuing exodus of high-value jobs and highly-skilled professionals, and warns policymakers that these trends will threaten the competitive advantage of the United States in global competition and slow down its economic development in the long run. In the context of developing and emerging economies, evidence for the positive impact of the new Argonauts[54] on the economic development of their countries of origin (Saxenian, 2007) has been found. Thus, how developing countries utilize brain circulation and capitalize on it by "brain gain" and how developed countries respond to talent flight are critical to the interests of each country (Florida, 2005; Saxenian, 2007; Thorn & Holm-Nielsen, 2006).

As illustrated in the 77 CKM profiles, the majority of moderators residing in China have overseas experience. This study highlighted the heightened positive impact of scholars who have had the opportunity to work in the US as opposed to those who have visited the US sponsored by Chinese government (Hypothesis 5). This finding was relevant to the policy debate on inviting in the "sea turtle" (*haigui*) or sending out the "domestic turtle" (*tubie*).[55] According to the statistics released by the China Scholarship Council, in 2010 alone, the Chinese government selected and funded 12,000 scholars and students to study or visit overseas with varying terms from 3 to 48 months.[56] Given the large number of visiting students/scholars funded by the Chinese government, the efficiency and effectiveness of how money is spent, a topic beyond the scope of this discussion, is worthy of further exploration.

It should be noted that the purpose of this paper was not to make a statistical generalization. However, the case of US-China scientific collaboration in nanotechnology served as a framework within which we could examine the role of international collaboration on the knowledge accumulation of a developing country. All of these experiences and lessons of China

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[54] Saxenian transforms the concept of Argonauts and refers to them as technically-skilled entrepreneurs who "sail" back and forth between their home countries and Silicon Valley.

[55] Overseas returnees, or *haigui* in Chinese, are often labeled with its homophone meaning "sea turtles." *Tubie*, the homophone referring to "ground beetles," refers to professionals trained in China who compete for jobs with the returnees (Louie, 2006).

[56] Source: http://en.csc.edu.cn

may have policy implications for other developing countries as they endeavor to catch up with advanced economies through international collaboration.

Although this paper focused on China, it has policy implications for the US. The evidence of China's rise in science is indisputable. The positive impact of US-China collaboration does not necessarily indicate the loss of US American competitiveness as a result of collaboration with China. In fact, a number of studies have suggested that foreign-born scientists and engineers play a major role in scientific and innovation output in the United States (No & Walsh, 2010). The US should take advantage of and gain access to China's heavy R&D investment in this promising domain and tap into China's talent pool to carry on R&D activities benefiting the US industry and commercialization. The study found that the US actively collaborates with elite Chinese PRI in research domains in which China is traditionally strong. Thus, collaborating with top Chinese scientists can also serve as an effective way of monitoring the development of science and technology in this rising country, not to mention the transmission of ideological values and the exploration of an enormous market. On the other hand, concerns that America is losing its competitiveness have arisen. As international knowledge spillover associated with international collaboration is inevitable, anticipated knowledge spillover across national borders, particularly in some critical technologies, has implications for S&T and immigration policy in the US.

Future Research

This study, focusing on the *event* of "US-China collaboration," explored its impact on China's research performance in nanotechnology. Another angle from which we can examine this topic is to focus on the *individual*, the knowledge carrier. For a deeper understanding of the mechanisms that facilitate or block knowledge flow across national borders, qualitative studies that examine collaborations among international scientists are critical.

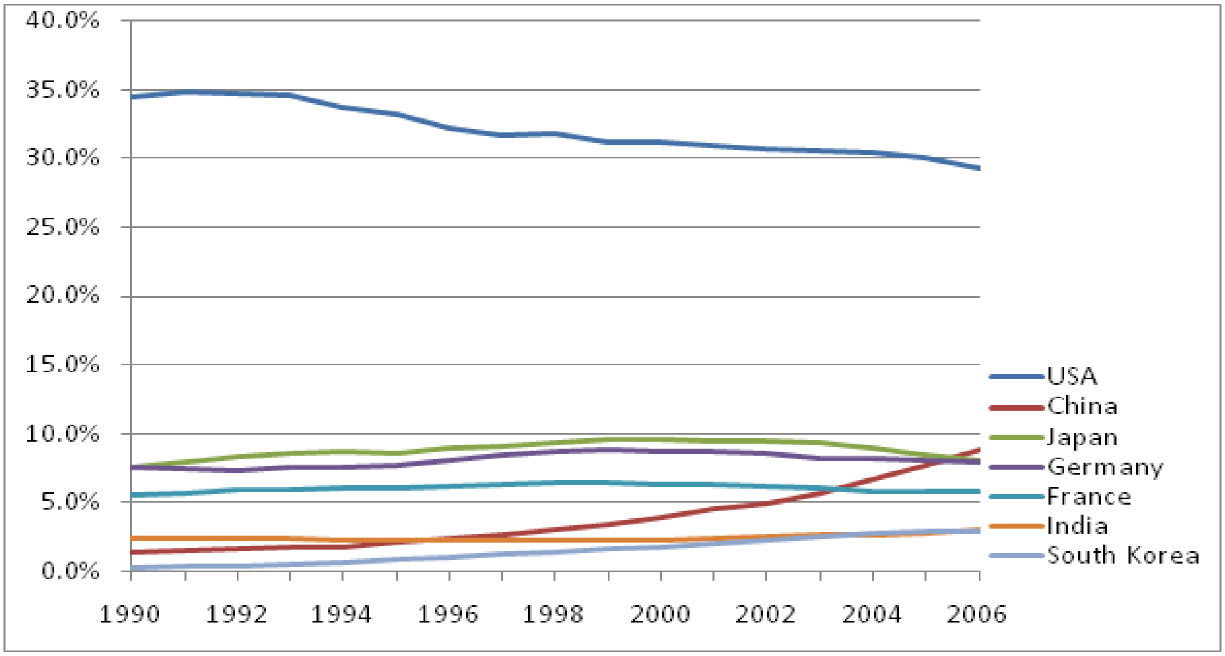
Two aspects warrant further exploration. One is a comparative study to explore the costs and benefits of international collaboration for both Chinese and US nanoscientists. Both benefits and costs of international collaboration have been explored extensively in previous research. What we already know is that individual scientists generally need to collaborate since no single individual is capable of possessing all the resources and expertise required to stay abreast of rapidly advancing technology, increasingly complex problems, and highly specialized research areas. What we barely know is whether all this is still the case in emerging technology, and if any differences exist across different country contexts (such as the US and China). Thus, a future research direction might explore this topic from the perspectives of Chinese and US American scientists based on surveys and case studies.

An associated line of comparative research could explore the motivators of and barriers to international collaboration. I agree with Wagner and Leydesdorff's statement that the "preferential attachments" with "continuant" scientists from advanced economies may contribute to increased research visibility in China (Wagner & Leydesdorff, 2005). The self-organizing nature of collaboration, however, indeed suggests that the initiation and maintenance of this bilateral relationship requires mutual benefits. Another research direction is to investigate how international collaborators from both countries perceive motivators and barriers. Such research would explore and compare such motivations (institutional or individual) and the mechanism of cross-border collaboration from the perspective of both Chinese and US nanoscientists. How the general characteristics and special features of sub-domains of nanotechnology impact international collaboration behavior and mechanism could be explored through interviews.

In addition to qualitative research, another direction for future study is to refine the method of identifying research streams and their correlation with international collaboration. This method was applied to three researchers and produced reasonably reliable results. For future research, the method can be refined by adding two weighting mechanisms based on the frequency of the appearance of keywords within a specific domain and the number of keywords in each article. In future work, this method can be applied to large-scale archival data to identify the evolution of research on the national level. The clustering results can be also applied to identify either domestic or international colleagues who are pursuing the same research and who may potentially collaborate for resource mobilization.

APPENDICES

APPENDIX A.1: Publication Shares of the Seven Most Productive Countries



Note. Calculated by the author based on information downloaded from SciSearch at Fraunhofer ISI, Germany. Whole counting is used here.

APPENDIX B.1:Georgia Tech Modular Nano Search Algorithm

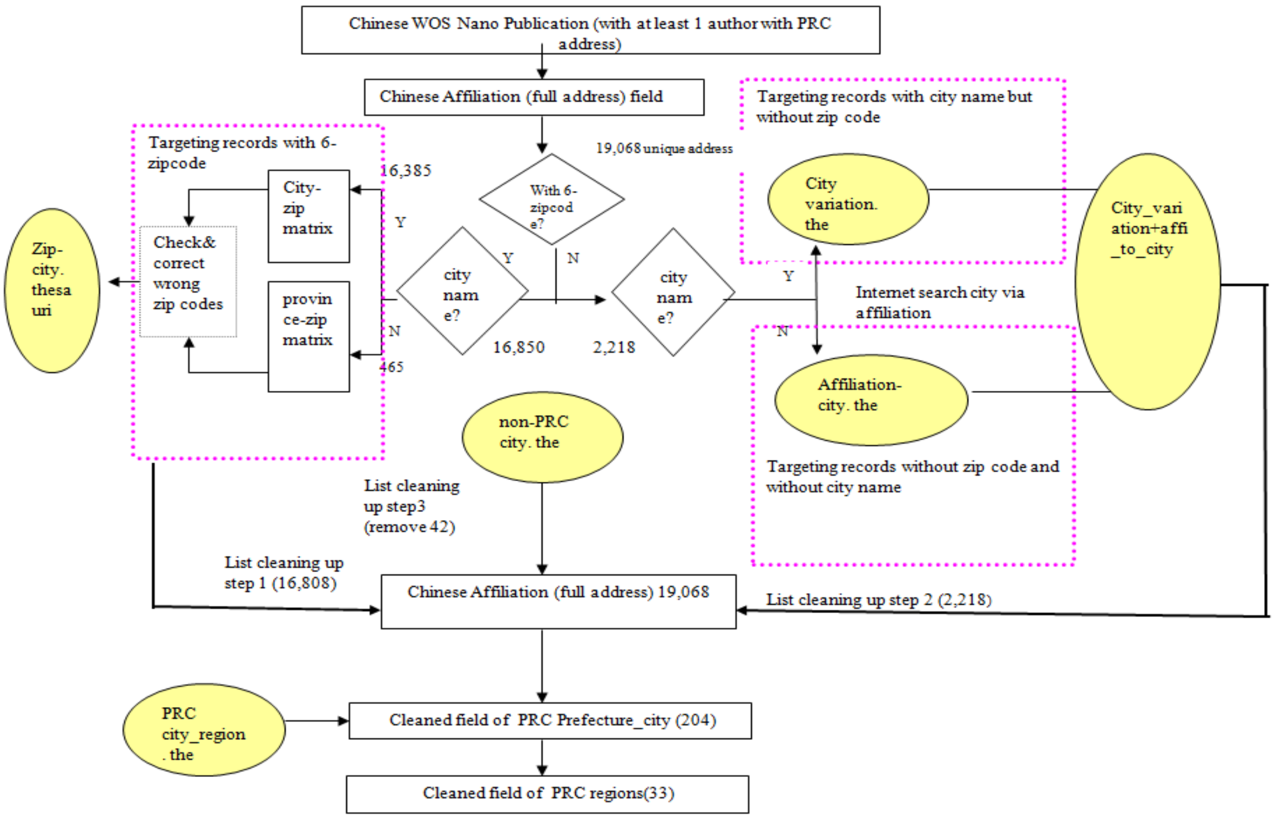
Search	Terms	RESULT:SCI 2005 as of 4/22/06
MolEnv-I (inclusive)	(monolayer* or (mono-layer*) or film* or quantum* or multilayer* or (multi-layer*) or array* or molecul* or polymer* or (co-polymer*) or copolymer* or mater* or biolog* or supramolecul*)	>100,000
Or		
MolEnv-R (more restrictive	(monolayer* or (mono-layer*) or film* or quantum* or multilayer* or (multi-layer*) or array*)	78,390
And		
1. Nano*	nano*	39,101
2. Quantum	(quantum dot* OR quantum well* OR quantum wire*) NOT nano*	3,633
3. Self-Assembly	(((SELF ASSEMBL*) or (SELF ORGANIZ*) or (DIRECTED ASSEMBL*)) AND MolEnv-I) NOT nano*	3,532
4. Terms to include as Nano without other delimiters	((molecul* motor*) or (molecul* ruler*) or (molecul* wir*) or (molecul* devic*) or (molecular engineering) or (molecular electronic*) or (single molecul*) or (fullerene*) or (coulomb blockad*) or (bionano*) or (langmuir-blodgett) or (Coulomb-staircase*) or (PDMS stamp*)) NOT nano*	3,550
5. Microscopy - terms to include but limit to the molecular environment	((TEM or STM or EDX or AFM or HRTEM or SEM or EELS) or (atom* force microscop*) or (tunnel* microscop*) or (scanning probe microscop*) or (transmission electron microscop*) or (scanning electron microscop*) or (energy dispersive X-ray) or (X-ray photoelectron*) or (electron energy loss spectroscop*)) AND MolEnv-I) NOT nano*	11,665
6. Nano-pertinent; Limit to the Molecular Environment - More Inclusively	(pebbles OR NEMS OR Quasicrystal* OR (quasi-crystal*)) AND MolEnv-I) NOT nano*	128
7. Nano-pertinent; limit to the Molecular Environment - More Restrictive	(biosensor* or (sol gel* or solgel*) or dendrimer* or soft lithograph* or molecular simul* or quantum effect* or molecular sieve* or mesoporous material*) AND (MolEnv-R)) NOT nano*	2,104
	1 or 2 or 3 or 4 or 5 or 6 or 7	61,173
8. Additional Items in Nano Journals	fullerene* or ieee transactions on nano* or journal of nano* or nano* or materials science & engineering C - biomimetic and supramolecular systems (in JOURNAL title field) NOT nano*	506
Total	1 or 2 or 3 or 4 or 5 or 6 or 7 or 8	61,479

Source: Porter et al. (2008). Table 2, page 721.

APPENDIX B.2: Available Information for US-China Publication in WoS

Field	Field_Name	No. of Items	% Coverage
Unique SCI-WoS ID	ISI Unique Article Identifier	2061	100%
Address	Affiliation (City and Country) (Cleaned)	578	100%
	Affiliation (Full)	3431	100%
	Affiliation (Name Only) (Cleaned)	988	100%
	Countries	80	100%
	Countries (cleaned)	42	100%
	Country (1st)	49	100%
	Country (1st) (cleaned)	24	100%
	Reprint Address-full	1632	98%
Author	Authors	5268	100%
	Author (1st)	1332	100%
	Primary authors (Single Author + Reprint Author)	1395	100%
	Email	701	45%
Keywords	Combined Keywords + Phrases	49528	100%
	Keywords (author's)	2828	44%
	Keywords Plus	4980	95%
	Keywords (author's) + Keywords Plus (Cleaned) (Cleaned) (Cleaned)	6043	98%
	Subject Category	108	99%
Collaboration Scope	No. of Affiliation (Full)	11	100%
	No. of Affiliation (Name Only)	11	100%
	No. of Authors	39	100%
	No. of Countries	12	100%
Publication Time	Publication Date	351	93%
	Publication Type	2	100%
	Publication Year	17	100%
Forward citation	Times Cited	670	100%
Journal	ISSN	445	100%
	Journal	441	99%
	Publisher	164	100%
	Publisher (Short)	164	100%
	Publisher City	99	100%
	Source	457	100%
	Source (Start Page)	1342	89%
	Source (Volume)	364	98%
	Source Title (Abbrev)	446	100%
Others	Document Type	1	100%
	Language	3	100%
	~Raw Record	2061	100%
	Pages	31	100%
	ISI Doc Delivery Num	1881	100%

APPENDIX B.3: Geographical Cleaning Framework of Chinese Nano Publications



Appendix B.3 details the cleaning process and subjective judgments on geographical information standardization for Chinese nano publication dataset. Although theoretically one city has many ZIP codes, one ZIP code should be assigned to only one city. In the downloading from SCWE-WoS, however, many cases in which a single zip code is associated with different city names have been found. This situation is complicated by different meanings of the concept of "city." In China, four different levels of cities exist. The first-level cities are the municipalities of Beijing, Tianjin, Chongqing, and Shanghai, plus Hong Kong and Macau (two special administrative regions). These six cities enjoy the same administrative status as provinces (equivalent to states in the US). The second-level category of cities comprises 33 provincial capital cities. The third level category of cities consists of 283 prefecture cities at sub-provincial level. And the fourth-level category consists of 374 county-level cities nationally. Thus, if one

ZIP code is associated with different city names, one possible reason is that this ZIP code is used for different levels of cities. If this situation is not corrected before analysis, it could cause errors in analyzing the spatial shifts of nano research.

The following solution was adopted: I first left the city name as it appeared in WoS to avoid information loss by data aggregation. Once we were certain that a city evolved from a county,[57] we matched it with its immediate parent prefectural city and created a new field, "Prefecture level city, China," in which all the county-level cities were replaced with their immediate supervising prefecture cities.[58] By standardizing all the cities in the dataset in this way, we compiled a final dataset of 204 cities. We further categorized the cities into provinces for a cross-check. To identify any inconsistencies, including missing data on the provincial level,[59] a second check was run on the raw records to address this problem separately.

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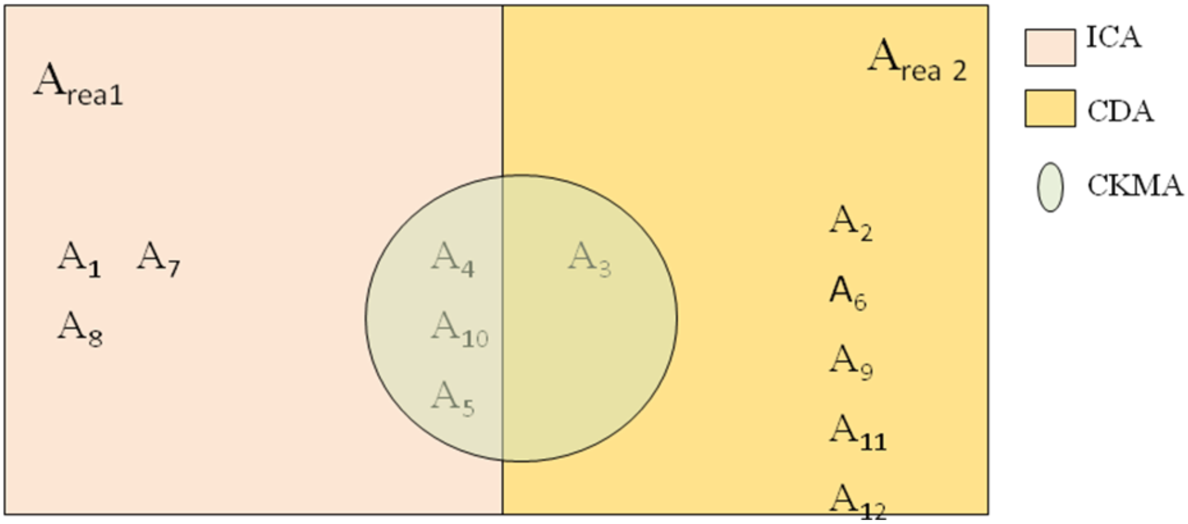
[57] This was quite popular in China in the 1990s. To stimulate development in rural areas, some counties were updated to county-level cities.

[58] Considering both economic autonomy level and geographical coverage, we think the prefecture city is the most appropriate level of a city for analysis. This aggregation approach is also consistent with OECD patent area aggregation rules. For more details, please refer to STI work paper by Maraut *et al*.

[59] For those records incorrectly assigned to China (such as Korean, Taiwanese, and Japanese publications), the province data remained blank.

APPENDIX B.4: Graphic Illustration of CDA, ICA, and CKMA



APPENDIX B.4 is a graphic illustration of CKMAs and ICAs. CDA represents Chinese domestic papers, ICA stands for international collaborative papers, and CKMA refers to articles involving Chinese knowledge moderators. Area 1 represents the set of international collaborative articles (ICA) between China and the US, where ICA= {A1, A4, A5, A10}. Area 2 represents the set of Chinese domestic articles (CDA), and CDA= {A2, A6, A, A9, A11, A12}. The ellipse is the collection of China-US CKMA, in which CKMA= {A1, A2, A10}. As shown in APPENDIX B.4, CKMA includes some papers that appeared in either ICA or CDA. To be more specific, the research papers included in the right side ellipse, namely (CKMA ∩ ICA) are those written by Chinese overseas returnees and/or researchers who have joint appointments in both countries. It is reasonable to believe that those articles embed international knowledge diffusion from the US American side when other Chinese authors are involved. That is, using ICA alone, that means ignoring Area 3 entirely—leads to a biased downward estimation of the impact of international knowledge spillover on China's knowledge accumulation.

APPENDIX B.5: Identified CKMs and CKMA Before vs. After Validation

Sub-area	CKM_ID	Reported Name in WoS	Full Name	Chinese Name	# Pubs Before Cleaning	# Pubs After Cleaning
Mat	101	Wang, Z L	Wang, Zhong Lin	王忠林	108	55
Mat	102	Xu, W B	Xu,Wei Bing	徐卫兵	19	19
Mat	104	An, L N	An, Li Nan	安立楠	15	13
Mat	106	Zu, X T	Zu, Xiao Tao	祖小涛	16	16
Mat	107	Li, X G	Li, Xin Gui	李新贵	110	13
Mat	108	Li, X Y	Li, Xin Yong	李新勇	81	34
Mat	110	Wu, M M	Wu, Ming Mei	吴明娒	21	9
Mat	111	Zhang, W J	Zhang, Wan Jin	张万金	79	25
Mat	112	Chen, X T	Chen, Xue Tai	陈学太	19	14
Mat	113	Li, P	Li, Pei	李蓓	82	23
Mat	114	Li, Y H	Li, Yan Hui	李延辉	80	33
Mat	115	Liu, H	Liu, Hong	刘宏	134	31
Mat	116	Wan, MX	Wan, Mei Xiang	万梅香	83	8
Mat	117	Guan, N J	Guan, Nai Jia	关乃佳	8	8
Mat	118	Wei, Y	Wei, Yen	危岩	171	74
Mat	119	Jiang, Q	Jiang, Qin	蒋青	98	87
Mat	120	Lu, Y F	Lu, Yun Feng	陆云峰	22	17
Mat	121	Meng, G W	Meng, Guo Wen	孟国文	103	103
Mat	122	Zou, B S	Zou, Bin Shuo	邹炳锁	70	69
Mat	123	Nan, C W	Nan, Ce Wen	南策文	57	57
Mat	125	Wan, L J	Wan, Li Jun	万立骏	143	143
Mat	126	Wang, J Q	Wang, Jian Qi	王建祺	33	18
Mat	127	Xie, Y	Xie, Yi	谢 毅	257	236
Mat	128	Xin, Q	Xin, Qin	辛 勤	36	36
Mat	129	Yang, Z Z	Yang, Zhenzhong	杨振忠	39	35
Mat	130	Fang, J Y	Fang, Ji Ye		12	5
Bio	201	Tan, W H	Tan, Wei Hong	谭蔚泓	22	22
Bio	202	Yang, Y Z	Yang, Yun Zhi		21	3
Bio	203	Zhou, FM	Zhou, Fei Meng		11	9
Bio	204	Mao, H Q	Mao, Hai Quan	毛海泉	2	2
Bio	205	Pang, D W	Pang, Dai Wen	庞代文	41	41
Bio	206	Hu, N F	Hu, Nai Fei	胡乃非	32	32
Bio	207	Chen, J H	Chen, Jin Hua	陈金华	51	38
Bio	208	Chen, T H	Chen, Tian Hu	陈天虎	20	7

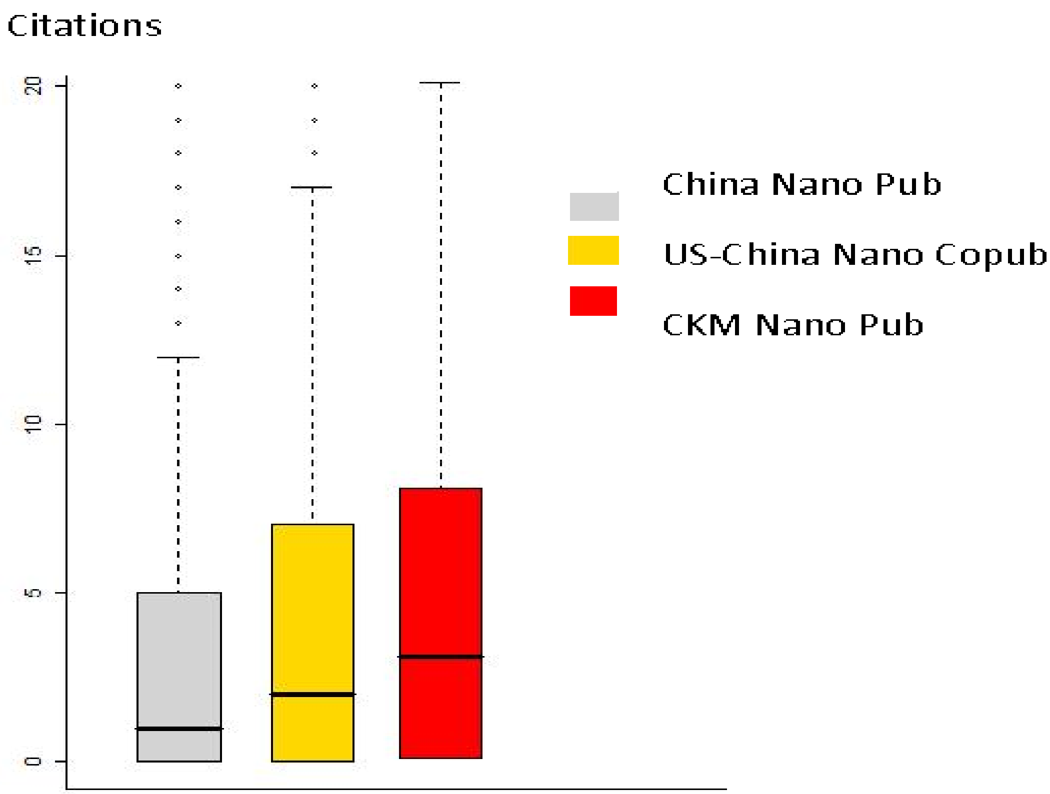
Appdendix B.5 Continued

Bio	209	Fei, W Y	Fei, Wei Yang	费维扬	6	6
Bio	212	Gao, C Y	Gao, Chang You	高长有	45	42
Bio	214	Wang, J	Wang, Jin	王进	599	32
Bio	215	Chen, X S	Chen, Xue Si	陈学思	78	24
Bio	216	Li, G X	Li, Gen Xi	李根喜	53	34
Bio	218	Xu, H F	Xu, Hui Fang		22	11
Bio	219	Zhang, J	Zhang, Ji	张济	407	4
Bio	220	Ji, J	Ji, Jian	计剑	38	35
Bio	221	Jiang, H L	Jiang, Hong Long	蒋宏亮	16	11
Bio	222	Xia, Y N	Xia, You Nan	夏幼南	11	11
Bio	224	Zou, H F	Zou, Han Fa	邹汉法	17	17
Bio	225	Wang, J X	Wang, Jian Xiu	王建秀	118	10
Bio	227	Chang, J	Chang, Jiang	常江	24	16
Bio	228	Dong, C M	Dong, Chang Ming	董常明	4	4
Bio	229	Ma, Y F	Ma, Yin Fa		7	3
Elec	301	Ren, S F	Ren, Shang Fen		18	14
Elec	302	Zhang, J	Zhang, Jin		407	3
Elec	303	Luo, G A	Luo, Guo An	罗国安	41	35
Elec	304	Wang, C	Wang, Ce	王策	308	36
Elec	305	Wu, Y Z	Wu, Yi Zheng	吴义政	24	10
Elec	306	Zheng, JW	Zheng, Jun Wei	郑军伟	23	12
Elec	307	Zhao, J J	Zhao, Ji Jun	赵纪军	35	32
Elec	308	Cao, Y	Cao, Yong	曹镛	129	21
Elec	309	Chen, W	Chen, Wei		178	12
Elec	310	Chen, X	Chen, Xi	陈曦	152	13
Elec	311	Wang, E G	Wang, En Ge	王恩哥	119	117
Elec	312	Chen, Y F	Chen, Yun Fei	陈云飞	98	9
Elec	313	Chen, Z F	Chen, Zhong Fang		42	29
Elec	314	Dong, B	Dong, Bin	董兵	40	20
Elec	315	Lin, J	Lin, Jun	林君	93	60
Elec	316	Lin,Y H	Lin, Yue He	林跃河	56	6
Elec	317	Liu, Y C	Liu, Yi Chun	刘益春	156	108
Elec	318	Qiu, K Y	Qiu, Kun Yuan	丘坤元	30	30
Elec	319	Shen, W Z	Shen, Wen Zhong	沈文忠	62	55
Elec	320	Tang, W H	Tang, Wei Hua	唐为华	27	26
Elec	321	Wang, B L	Wang, Bao Lin	王保林	34	21

Appendix B.5 Continued

Elec	322	Wang, H	Wang, Hui	王辉	369	2
Elec	323	Wang, HY	Wang, Huaiyu	王怀玉	66	7
Elec	324	Yang, W Y	Yang, Wei You	杨为佑	20	9
Elec	325	Zeng, X C	Zeng, Xiao Cheng	曾晓成	5	3
Elec	326	Chen, D P	Chen, De Pu	陈德朴	26	16
Elec	327	Wang, G H	Wang, Guang Hou	王广厚	133	117
Elec	328	Lu, X C	Lu, Xin Chun	路新春	23	14

APPENDIX C.1: Citation distribution boxplot of Chinese nanotechnology papers by authorship type



APPENDIX C.2: List of Chinese Elite Universities

Rank	**Elite University of China**	**City**
1	Tsinghua University	Beijing
2	Beijing University	Beijing
3	Zhejiang University	Hangzhou
4	Fudan University	Shanghai
5	Nanjing University	Nanjing
6	Univ Sci & Technol China	Hefei
7	Shanghai Jiao Tong University	Shanghai
8	Wuhan University	Wuhan
9	Jilin University	Changchun
10	Harbin Institute of Technology	Harbin

Source: *The 21st Century Business Herald*, *China Daily*, February 21, 2005.

APPENDIX D.1: Hausman-Wu Specification Test

	(b) fixed_effe~s	(B) random_eff~s	(b-B) Difference	sqrt(diag(V_b-V_B)) S.E.
USCOLLAB	-0.83	-1.46	0.62	0.83
*USCOLLAB*PUB-AGE*	1.40	1.30	0.09	0.50
NUSCOLLAB	2.01	1.78	0.23	0.86
*NUSCOLLAB * PUB-AGE*	0.04	0.19	-0.15	0.55
CHINESE	-4.12	-5.04	0.92	0.20
HONG KONG	1.55	-2.10	3.65	0.50
CAS	-0.32	0.91	-1.24	0.94
ELITE-UNIV	0.64	-0.05	0.69	1.62
AFFILIATIONS	0.71	0.49	0.22	0.57
PRC-CITY	-1.64	-1.23	-0.41	1.26
AUTHORS	0.18	0.22	-0.05	0.15
PUB-AGE	2.14	2.17	-0.03	0.12

b = consistent under Ho and Ha; obtained from xtreg

B = inconsistent under Ha, efficient under Ho; obtained from xtreg

Test: Ho: difference in coefficients not systematic

chi2(12) = (b-B)'[(V_b-V_B)^(-1)](b-B)

= 29.52

Prob>chi2 = 0.0033

(V_b-V_B is not positive definite)

APPENDIX D.2 Wald Test for the Joint Impact of Researcher Capacity

(1) HONG KONG = 0

(2) CAS = 0

(3) ELITE-UNIV = 0

F(3, 2097) = 1.64

Prob > F = 0. 1772

APPENDIX E.1: Publications of Zu, Xiao Tao, in Nanotechnology (1990–2006)

Code	Cluster	Year_Ctry	Title
AU1	1	2001, China	Experimental research of laser-induced damage mechanism of the sol-gel SiO2 and ibsd SiO2 thin films
AU2	1	2003, China; USA	Hydrogen embrittlement of a Ti-Al-Zr alloy evaluated by impact test method
AU3	1	2004, China; USA	Investigation on technological process of preparation of TiO2 nanocrystal for rutile crystal growth
AU4	1	2005, China	Irradiation-induced martensitic transformation of TiNi shape memory alloys
AU5	1	2005, China	Magnetic nano-particles of Ni in MgO single crystals by ion implantation
AU6	1	2005, China; USA	Optical and magnetic properties of Ni nanoparticles in rutile formed by Ni ion implantation
AU7	1	2005, China; USA	Optical and magnetic properties of Ni/NiO nanoparticles in YSZ by metal ion implantation and post-implantation annealing
AU8	1	2006, China	Optical properties and structure characterization of sapphire after Ni ion implantation and annealing
AU9	1	2006, China	Optical properties of metallic nanoparticles in Ni-ion-implanted alpha-Al2O3 single crystals
AU10	1	2006, China	Origin of luminescence from PMMA functionalized nanoparticles
AU11	1	2006, China; USA	Photoconductive UV detectors based on ZnO films prepared by sol-gel method
AU12	1	2006, China; USA	Photoluminescence from TiO2/PMMA nanocomposite prepared by gamma radiation
AU13	1	2006, China; USA	Preparation and characterization of polymer/inorganic nanoparticle composites through electron irradiation
AU14	1	2006, China; USA	Structural and magnetic characterization of CoxNi1-x nanoparticles in yttria-stabilized zirconia single crystals
AU15	2	2004, China; USA	Surface modification on nanoscale titanium dioxide by radiation: Preparation and characterization
AU16	3	2004, China; USA	TEM observation of oxide scale formed on a Ti-Al-Zr alloy oxidized at 360 degrees C in alkaline steam

APPENDIX E.2: Evidence of Extended Knowledge Spillover from Authors and Affiliations: Zu, Xiao Tao

Publication Year	**2003**	**2004**	**2005**	**2006**
Authors	Ewing, R C	Wang, L M	Bao, J W	Fang, L M
	Sun, K	Xiang, X	Wang, L M	Jiang, B
	Wang, L M	Zhu, S	Xiang, X	Lian, J
	Zhang, Q Y	Zu, X T	Zhu, S	Lu, J
	Zhu, S		Zu, X T	Tang, F Y
	Zu, X T			Wang, L M
				Wang, Z G
				Wei, Q R
				Wu, Z H
				Xiang, X
				Yu, H J
				Zhang, X D
				Zhu, S
				Zu, X T
Author_Affiliations	Dalian Univ Technol	Univ Elect Sci & Technol China	Chinese Acad Sci	Sichuan Univ
	Univ Elect Sci & Technol China	Univ Michigan	Univ Elect Sci & Technol China	Univ Elect Sci & Technol China
	Univ Michigan		Univ Michigan	Univ Michigan

Note: Cells highlighted in grey are those newly appearing in publications on the subject among authors or affiliations compared to the base year of 2003.

APPENDIX E.3: Publications of Chen, De Pu, in Nanotechnology (1990–2006)

Code	Cluster	Year_Ctry	Title
AR1	1	2006, China	Experimental research of laser-induced damage mechanism of the sol-gel SiO2 and ibsd SiO2 thin films
AR2	2	2005, China	Hydrogen embrittlement of a Ti-Al-Zr alloy evaluated by impact test method
AR3	3	2001, China	Investigation on technological process of preparation of TiO2 nanocrystal for rutile crystal growth
AR4	4	2004, China; USA	Irradiation-induced martensitic transformation of TiNi shape memory alloys
AR14	5	2003, China; USA	Structural and magnetic characterization of CoxNi1-x nanoparticles in yttria-stabilized zirconia single crystals
AR9	5	2004, China; USA	Optical properties of metallic nanoparticles in Ni-ion-implanted alpha-Al2O3 single crystals
AR7	5	2005, China; USA	Optical and magnetic properties of Ni/NiO nanoparticles in YSZ by metal ion implantation and post-implantation annealing
AR8	5	2005, China; USA	Optical properties and structure characterization of sapphire after Ni ion implantation and annealing
AR12	5	2006, China	Photoluminescence from TiO2/PMMA nanocomposite prepared by gamma radiation
AR15	5	2006, China	Surface modification on nanoscale titanium dioxide by radiation: Preparation and characterization
AR5	5	2006, China; USA	Magnetic nano-particles of Ni in MgO single crystals by ion implantation
AR6	5	2006, China; USA	Optical and magnetic properties of Ni nanoparticles in rutile formed by Ni ion implantation
AR10	5	2006, China; USA	Origin of luminescence from PMMA functionalized nanoparticles
AR13	5	2006, China; USA	Preparation and characterization of polymer/inorganic nanoparticle composites through electron irradiation
AR11	6	2005, China	Photoconductive UV detectors based on ZnO films prepared by sol-gel method
AR16	7	2004, China; USA	TEM observation of oxide scale formed on a Ti-Al-Zr alloy oxidized at 360 degrees C in alkaline steam

APPENDIX E.4: Publications of Ya Dong Jiang in Nanotechnology (1990–2006)

Code	**Cluster**	**Year_Ctry**	**Title**
AR1	1	2003, China	A novel microsensor fabricated with charge-flow transistor and a Langmuir-Blodgett organic semiconductor film
AR2	1	2003, China	A novel NO2 gas sensor based on bis[phthalocyaninato] samarium complex/silicon hybrid charge-flow transistor
AR3	1	2001, China	A study on erbium bis[octakis(octyloxy)phthalocyaninato] sandwich complex based gas-sensitive Langmuir-Blodgett films
AR4	1	2003, China	Erbiurn bis[phthalocyaninato] complex LB film gas sensor
AR5	1	2002, China	Fabrication and characterization of polyaniline-based gas sensor by ultra-thin film technology
AR6	1	2000, China	Fabrication of a prototype humidity-sensitive capacitor via layer-by-layer self-assembling technique
AR7	1	2000, China	Fabrication of self-assembled polyaniline films by doping-induced deposition
AR8	1	2001, China	Gas sensitive Langmuir-Blodgett films based on erbium bis[octakis(octyloxy)phthalocyaninato] complex
AR9	1	2001, China	Preparation and gas-sensing property of polyaniline based ultrathin films by Langmuir-Blodgett technology
AR10	1	2000, China	Self-assembly of polyaniline ultrathin films based on doping-induced deposition effect and applications for chemical sensors
AR11	1	1999, China	Study on biological molecular LB films and properties
AR12	1	2002, China	Study on bis[phthalocyaninato] praseodymium complex/silicon hybrid chemical field-effect transistor gas sensor
AR13	1	2001, China	Study on the characteristics and relative properties of Langmuir-Blodgett films based on substituted bis[phthalocyaninato] rare earth(III) complexes
AR14	1	2003, China	The properties of praseodymium bis[octakis(octyloxy)phthalocyaninato] complex Langmuir-Blodgett films for NO2 sensor

APPENDIX E.5: LSTAT Ouptut for Probit Regression on Shifting Research Topic

```
                  Probit model for delta

                         -------- True --------
Classified |         D             ~D  |      Total
-----------+---------------------------+-----------
+          |         6              0  |          6
-          |       367           1746  |       2113
-----------+---------------------------+-----------
Total      |       373           1746  |       2119

      Classified + if predicted Pr(D) >= .5
           True D defined as delta != 0
--------------------------------------------------
Sensitivity                     Pr( +| D)    1.61%
Specificity                     Pr( -|~D)  100.00%
Positive predictive value       Pr( D| +)  100.00%
Negative predictive value       Pr(~D| -)   82.63%
--------------------------------------------------
False + rate for true ~D        Pr( +|~D)    0.00%
False - rate for true D         Pr( -| D)   98.39%
False + rate for classified +   Pr(~D| +)    0.00%
False - rate for classified -   Pr( D| -)   17.37%
--------------------------------------------------
Correctly classified                        82.68%
--------------------------------------------------
```

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